A SURVEY AND CRITIQUE OF TECHNOLOGICAL FORECASTING METHODS

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THESIS

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ABSTRACT

A critical survey of technological forecasting techniques is presented. The nature of technological forecasting permits the various techniques to be classified as intuitive, exploratory, and normative. Intuitive technological forecasting is based on the informal use of exploratory and normative techniques, including the forecaster's biases and hunches. Exploratory technological forecasting starts from a present empirical or theoretical basis of knowledge and is oriented towards the future. Normative technological forecasting, on the other hand, first assesses future goals and missions and works backward to the present. Some pitfalls of technological forecasting are discussed. The most essential are: (1) a lack of imagination on the part of the forecaster; (2) a belief that the human intellect can create anything it can conceive; (3) a lack of consideration of seemingly unrelated factors; and (4) the use of inappropriate techniques or incorrect calculations. Factors which should be considered in selecting a forecasting technique are suggested and include: (1) the circumstances under which the forecaster is working; (2) the characteristics of the data base; (3) and the time available for generating the forecast.

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I. INTRODUCTION

The author of this paper has been interested for some time in the process by which the Department of Defense acquires new systems. Before a new system becomes operational many decisions are made concerning alternative technical approaches, alternative force sizes, length of the research and development phase, and the like. In many, if not most of these decisions, the author believes that a particularly important information input concerns the state of future technology.

In developing information about the state of future technology, it becomes necessary to forecast what will, or at least what could be available, based on information about the state of current technology. Thus the author was led to reviewing the literature on technological forecasting in an effort to study the techniques available for providing information about the future state of technology. It is the purpose of this paper to examine, in the form of a critical survey, these technological forecasting techniques and in so doing give an account of the state of the art of technological forecasting.

As indicated, technological forecasting, which has developed gradually since the end of World War II, attempts to provide an indication of the future of science and technology. The author of this paper believes it has gained importance for the following two reasons. First, the rapid

growth of opportunity offered by the many advances in science and technology necessitates a high selectivity on the part of decision-makers both at the level of the individual firm, government agency, and on a national scale. Choice between alternative decisions may make all the difference in competitive performance. Second, science and technology are recognized as influences in the transformation of society and as such governments must strive to forsee the impacts which technological developments are likely to have on future society and to guide the application of new knowledge in the attainment of national goals.

The expenditure on both basic research and the development of its consequences for practical purposes, whether peaceful or military, is growing so rapidly that it becomes increasingly important, at least to this author, for government and industry to be clear and precise on what they are trying to do and to study wisely the best way of doing it. It follows that it becomes of great importance to direct development in the right directions, selecting only those alternatives which show promise. The essence of the information base for the art of directing development is technological forecasting.

Early attempts at technological prediction were not rigorous enough to be characterized as technological forecasting in the present usage of these words, since they are largely prophecies resting on opinion rather than systematic logic. Although the history of predictions gives one a

feeling for the progress of technology, the subject will not be treated in this paper.

There are perhaps as many definitions of technological forecasting as there are writers in the field. However, a definition of technological forecasting suggested by the author of this paper is as follows: Technological forecasting is the use of systems of logical analysis to induce probabilistic assessments of future developments and impacts of technology. Technology in this sense denotes the broad area of purposeful application of the contents of the physical, life, and behavioral sciences.

Technological forecasting is responsible for a profusion of literature. This author's review of the literature, however, revealed four well-written books which provide a broad overview of the techniques, applications and viewpoints espoused by most technological forecasting experts [1,2,3,4]. These four books are recommended as an excellent starting point for those interested readers wishing to delve further into the subject and are annotated in Appendix A of this paper.

The reader of technological forecasting literature is cautioned to the fact that there are a number of seemingly repititious articles as well as frequent cross-references in existence. This point should not lead to frustration, since comparison of the works usually reveals subtle differences in the author's concept and philosophy of technological forecasting.

A final word on the references used in this paper is appropriate. The List of References is confined to only those works cited in the paper. In addition to these references and the annotated bibliographies contained in References [1-4], there are three excellent bibliographies available to the reader [6,7,8].

Technological forecasting is not yet a science, but an art, Human judgment is enhanced, not replaced by it. If technological forecasting is to be useful in meaningful applications, it must be structured and developed in a proper framework. The conceptual framework utilized by many authors in the field is that of viewing the transfer of technology through various levels of development [5].

By way of explanation of this framework, the concept of technology must first be treated. The image of technology, until recently, was considered in terms of machines and equipment, i.e., hardware. Today, however, technology consists increasingly of software, i.e., the organization and systemization of ways of accomplishing tasks [5]. In this wider sense, the principles of management, when embodied in an organization or in a management system such as PERT, are just as much technology as a Polaris missile.

Technology transfer, for hardware or software, is the process by which science and technology are diffused throughout human activity [5]. This can be either transfer from basic scientific knowledge into technology (the so-called vertical transfer), or adaptation of an existing technology to a new use (the so-called horizontal transfer).

Vertical transfer refers to the transfer of technology moving through levels of development by which a "state of the art" becomes embodied in a system and by which the fusion of several different technologies leads to a new technology. Consider, for example, the recognition in solid-state theory of the fundamental concept of semi-conduction. This discovery in basic theory eventually led to integrated circuit technology, and further to solid-state communication systems and their impacts on the non-technical environment.

Horizontal transfer, on the other hand, occurs through the adaptation of a technology from one application to another. An example of this concept is the adaptation of a military aircraft to civilian air transport. Horizontal transfer may also include the transformation of laboratory procedures into medical care and the diffusion of military and space technologies into the commercial markets.

Technological forecasting is concerned with the forecasting of technological changes. If by technological change one understands the development of the applied sciences and their industrial exploitation, then forecasting will primarily be concerned with the capabilities provided by the changing state of the art, and their influence on the materials and techniques employed in industrial production. However, as mentioned before in the discussion of technology transfer, the term can also be used much more broadly to include the economic and social changes which result from the development of technology. It is unrealistic to discuss any aspect of technological change without

considering the social and economic environment in which it is expected to take place. It is the complexity of the interactions between changing technology and the complex and changing environment which presents technological forecasting with its most formidable difficulties.

The following three sections of this paper, in order of their presentation, contain a detailed discussion, including description, application and critique, of intuitive, exploratory, and normative forecasting techniques. Intuitive techniques may be categorized as individual or consensus (committee) forecasting. While a great deal of forecasting is attempted by the individual technique, the procedures of this method have not been formulated and will not be treated in this paper. The brainstorming technique, where a group of experts is gathered freely under the guidance of a moderator, is the first intuitive technique discussed. Because of the inherent difficulties in this method, the Delphi method was designed and is the subject of the remainder of Section II.

Exploratory technological forecasting starts from a present empirical or theoretical basis of knowledge and is oriented towards the future, i.e., it is opportunity-oriented. Normative technological forecasting, on the other hand, first assesses future goals, needs, and desires and works backward to the present, i.e., it is mission-oriented. This difference in orientation provided the author with a logical means of categorizing these techniques for presentation in the third and fourth sections.

The final section of this paper is a critical appraisal of technological forecasting in general. In particular, major pitfalls, criteria for selecting a method, and the future of forecasting are discussed.

II. INTUITIVE FORECASTING TECHNIQUES

A. INTRODUCTION

The title of this first chapter on forecasting techniques appears, at first glance, to be somewhat contradictory. Intuition is - according to Webster's New World Dictionary - "the immediate knowing or learning of something without the conscious use of reasoning." This definition of intuition seems to deny the possibility of applying any technique to the intuitive process. However, as Jantsch points out in studying supposedly intuitive forecasts of future technologies, one finds in general that they represent "cluttered pieces of systematic thinking" [1]. In short, although intuition is an undisciplined form of knowledge, it is not - as some would have it - the antithesis of rational analysis, nor should one imagine that intuition cannot be improved by the application of system and order.

Intuition is perhaps the oldest method of forecasting [9]. Until recently it was the only method, and now, after the development of other techniques, it is still widely used. Intuitive forecasting techniques may be categorized for convenience as individual forecasting or consensus forecasting.

The simplest of these two forms of intuitive forecasting is the individual or "prophet" forecast. If a certified "prophet" is available there is nothing more to say. If, however, either the "prophet" or "certification" is in question the modern tendency is to rely on consensus techniques.

The classic example of the so-called "prophet" is F. W. Lindemann, Churchill's powerful scientific advisor during World War II. He strongly advocated solid-fuel rocket propellants to the point that he refused to believe that the liquid-fuel German V-2 rocket could fly, despite photographic evidence to the contrary [4]. The author's review of the literature did not reveal any formal procedure for the individual forecasting technique and as a result this subject will not be treated in this section.

This section will include, however, a description, possible applications, and a critique of the various consensus techniques. In particular, the Delphi technique will be discussed in detail.

B. BRAINSTORMING

The first consensus technique is the brainstorming method, where a group of experts is gathered to speculate freely under the guidance of a moderator. The brainstorming technique is designed deliberately to create an environment conducive to speculation. The reason for this radical behavior is simply to alleviate the conservative nature of conventional type committees. Ayres cites the 1937 study of the National Research Council as an example of the effects of conservative forecasting [4]. The Council virtually missed all of the major developments of the decade, including antibiotics, radar, jet engines, and atomic energy.

Jantsch [1] offers the following basic rules for brainstorming sessions:

1. State the problem in basic terms, with only one focal point.

2. Do not find fault with, or stop to explore, any idea.

3. Reach for any kind of idea, even if its relevance may seem remote at the time.

4. Provide the support and encouragement necessary to liberate participants from inhibiting attitudes.

The moderator or group leader is responsible for reminding the participants of the above mentioned rules and encouraging uninhibited discussion. He also directs the interaction in such a way that the various opinions produced form a consensus.

A survey of the literature suggests that little has been published concerning the applications and effectiveness of this technique. One reason for this apparent lack of interest is the possible domination of the discussion by one person. A quite convincing series of studies have shown that the group opinion as used in the brainstorming scheme, is likely to be highly influenced, if not determined, by the views of the member of the group who does the most talking [10]. Another difficulty is the introduction of noise in the discussion. Noise is simply irrelevant or redundant material offered by the participants. A third difficulty is that group pressure has a tendency to overvalue reaching a consensus, i.e., the "bandwagon" effect of majority opinion.

The Delphi technique is designed to overcome these difficulties and is the subject of the following paragraphs.

C. DELPHI

Helmer and Dalkey of the Rand Corporation invented the Delphi method in the hope of rectifying the aforementioned difficulties of the brainstorming techniques [11]. In its simplest form, it eliminates committee activity among the experts altogether and replaces it with a carefully designed program of sequential, individual interrogations [2].

The Delphi procedure consists of three distinctive characteristics: anonymity, controlled feedback, and statistical group response [11]. Anonymity is a device to reduce the effect of the dominant individual. It is maintained by eliciting separate and private answers to prepared questions. Ordinarily, the procedure is carried out by written questionnaire or other formal communication channels, such as on-line computers. All other interactions between respondents is through formal communication channels controlled by the director of the forecast.

Controlled feedback is a device to reduce noise. This is accomplished by conducting the exercise in a sequence of rounds between which a summary of the results of the previous round are communicated to the participants.

The statistical group response is a device to assure that the opinions of every member of the group is represented in the final response. For cases where the group task is to estimate a numerical quantity, the median of individual estimates is the most useful index tried to date [11]. Thus, there is no particular attempt to arrive at unanimity among

the respondents, and a spread of opinions on the final round is the normal outcome. This is a further device to reduce group pressure toward conformity.

A typical exercise is initiated by a questionnaire which requests estimates of a set of numerical quantities, e.g., dates at which technological possibilities will be realized, probabilities of realization by given dates, or levels of performance. The results of the first round are summarized using the median and the interquartile range of the responses. The interquartile range is the interval containing the middle 50% of the responses. The results are then fed back to the participants with a request to revise the first estimates where appropriate. On succeeding rounds, those individuals whose answers deviate markedly from the median, e.g., outside the interquartile range, are requested to justify their estimates. These justifications are summarized, fed back, and counterarguments elicited. The counterarguments are in turn fed back and additional reappraisals collected.

The principles involved in this procedure can further be described by referring to a hypothetical example. Consider an inquiry into the future of automobiles in which each member of a panel of experts is asked to estimate the year (if ever) that they expect electric cars to capture ten percent of the automobile market.

The initial responses might consist of a set of estimates spread over a sizeable time-interval, i.e., from 1973 to 1998

with a median of 1990. A follow-up questionnaire feeds back to the respondents a summary of the distribution of these responses, stating the median and - as an indication of the spread of opinions - the interquartile range. The respondents are then asked to reconsider their previous answers and revise them if they so desire. If a new response lies outside the interquartile range, the particular respondent is asked to state his reason for thinking that the answer should be that much lower, or that much higher, than the majority judgment of the group.

Placing the onus of justifying relatively extreme responses on the respondents has the effect of causing those without strong convictions to move their estimates closer to the median, while those who feel they have a good argument for a "deviant" opinion tend to retain their original estimates and defend them.

In the next round, responses (now usually spread over a smaller interval) are again summarized and the respondents are given a concise summary of the reasons presented in support of extreme positions. They are then asked to revise their second-round responses, taking the preferred reasons into consideration and giving them whatever weight they think is justified. A respondent whose answer still remains outside the interquartile range is required to state why he is unpersuaded by the opposing arguments. In a fourth and final round, these criticisms of the reasons previously offered are resubmitted to the respondents, and they are given

a last chance to revise their estimates. The median of these final responses is then taken as representing the nearest thing to a group consensus. In the hypothetical case of the electric cars, this median might turn out to be the year 1985, with a final interquartile range from 1980 to 1990. The procedure therefore causes the median to move to a much earlier date and the interquartile range to shrink considerably, presumably influenced by convincing arguments. Bright's text contains an excellent example of an actual application of the Delphi method [2].

The hypothetical example presented above is intended to describe the basic procedures of the Delphi technique. A series of experiments were initiated at Rand to evaluate these procedures and to explore the nature of the information processes occurring in the Delphi interaction [11,12]. The two basic issues examined were a comparison of face-to-face discussion (Brainstorming) with the controlled feedback interaction (Delphi), and a thorough evaluation of controlled feedback as a technique for improving group estimates. The results of the study indicated that face-to-face discussion tends to make the group estimate less accurate, whereas, the anonymous controlled feedback procedure made the group estimates more accurate. "Accuracy" in this context refers to the distance of the median to the true answer. According to Dalkey, the experiment put the application of Delphi techniques in areas of partial information on much firmer ground [11].

Of greater long-range significance is the insight gained into the nature of the group information process. For example, Delphi procedures create a well-defined process that can be described quantitatively. In particular, the study found that the average error on round one is a function of the dispersion of the answers and the average amount of change of opinion between round one and round two is a well-behaved function of two parameters - the distance of the first-round answer from the group median, and the distance from the true answer.

Another result of major significance is that a meaningful estimate of the accuracy of a group response to a given question can be obtained by combining individual self-ratings of competence on that question into a group rating. This result, when combined with the relationship between accuracy and the median mentioned above opens the possibility of attaching accuracy scores to the products of a Delphi exercise [11].

The Delphi technique has been criticized in the past because it yields a set of "linearly independent" estimates of the future, i.e., the experts consider each event independently and omit consideration of the interaction among events. The experts unconsciously consider relationships among events, but they do not view the future as a set of interrelated paths. In an effort to improve this situation a "cross correlation" scheme is presently under investigation and has been employed by Gordon in a forecasting game

designed for Kaiser Aluminum and Chemical Corporation [2]. To describe this new approach consider that a list of developments are forecast, with varying levels of probability, to occur prior to a given year. If these developments are designated D_1, D_2, ..., D_n, with associated probabilities P_1, P_2,...,P_n, then the question can be posed: "If $P_i \to 1.00$, i.e., D_i occurs, how do P_1, P_2,...,P_n change"? If there is a "cross correlation", the probability of individual items will vary accordingly. In order to construct the game described above, a 60 x 60 matrix is reviewed for item cross correlations. If one considers a forecast with a thousand possible developments and that initial probabilities for each of these are established for a given year, it is plausible that the use of computers would greatly enhance the reviewing of such an extensive matrix.

The use of computers has also been instrumental in eliminating another shortcoming of the Delphi technique. For example, at the Rand Corporation the JOSS computer is used to control a series of simple Delphi studies [2]. JOSS is a centralized, general purpose computer which is programmed to accept English language instruction and has teletypewriter input/output stations at several remote locations in the Rand building. Gordon claims it is presently feasible to include participants located almost anywhere in the world in such computer controlled interactions.

The Delphi technique has proven extremely useful for long-range forecasting of expected technological and sociological developments such as political alliances, technological

potentials, war prevention techniques, and economic indices [2]. Results, as noted in Reference 2 for a limited number of cases, indicates consensus seems to have been achieved, the forecast was verified, and the potential developments which were described provided a basis for subsequent planning action. However, the reader is cautioned that in evaluating such forecasts one should remember at all times that they are intuitive. The evaluation must be made with respect to the forecast's authors, including the director or moderator. The moderator has great influence over the results of the forecast in that he chooses the experts, makes the initial decision of what events to include, and is also responsible for all the feedback to the experts.

The author of this paper notes that although there are many strengths and weaknesses of the Delphi method, its most valuable contribution to forecasting is its interaction with exploratroy and normative techniques. These techniques, built around the basic Delphi concept, provide a new set of approaches for the forecaster and a new flexibility for approaching problems which are not accessible to more direct methods of analysis. Taken together they indicate that the methodology of forecasting is only now being formulated and that in the near future these analytic methods will be sharpened, tested, and objectively used.

III. EXPLORATORY FORECASTING TECHNIQUES

A. INTRODUCTION

Exploratory technological forecasting starts from a present empirical or theoretical basis of knowledge and is oriented toward the opportunities of the future. This technique looks on the future in a general manner and follows the progress of a particular technology or all of technology as a function of time. In other words, exploratory forecasting is analogous to writing history in advance.

Exploratory techniques can be divided into two classes. The first class consists of the techniques which generate new technological information. These comprise two groups. First is extrapolation of time series (analytic and phenomenological and second is morphological analysis. The second class consists of techniques which structure and process given technological information. These include scenario writing, uncertainty techniques, cost/benefit analysis, operational models and input/output analysis.

The distinction between the two classes is important and therefore warrants further discussion. Since any complete technological forecasting process has to include techniques for generating some of the essential characteristics of future technologies, this aspect constitutes the oldest concern of technological forecasting. Jantsch points out that although it is the oldest, this class of exploratory forecasting is not at all satisfactory, and may even be said to be underdeveloped in relation to other forecasting aspects [1].

The other class of exploratory techniques, those structuring and processing given technological information, are relatively abundant. Jantsch predicts their importance will increase with the use of large-scale forecasting to evaluate large amounts of input data and programmed relationships [1]. He believes that this class of explorating forecasting will attain full importance only when technological forecasting is included in future systems of information technology.

This chapter includes a description of each of the previously mentioned techniques. The advantages, disadvantages and applications of each technique will also be included.

B. EXTRAPOLATION OF TIME SERIES

1. Analytic Models

Many quantitative characteristics exhibit an exponential or nearly exponential growth over time, with a subsequent flattening when a limit or saturation value is approached. For example, consider trends of specific techniques which enable a functional capability to be achieved. Initially the technique tends to experience a period of slow growth. It might be hidden in a laboratory at this time or buried in the patent office. Finally, its potential is recognized, money and labor are poured in, problems are solved, and an accelerated growth occurs. Eventually, limiting factors are encountered, the growth rate decelerates, and the curve asymptotically approaches some upper value. Explicit examples of this phenomena are presented in chronological order in the following paragraphs.

The extrapolation of time series constitutes perhaps the principal quantitative technique which is available to technological forecasting. The slope of the curve is usually forecast on the basis of a subjective belief, at least over short or medium time range, that the growth law of the past will also determine the future growth. Frequently this belief that past is prologue is called naive forecasting. The simple models presented in this section are intended to link the shape of technological growth curves to such factors as time in the hope that the generalization derived will yield a useful tool for quantitative trend extrapolation.

According to Lenz, attempts to develop a theory explaining why technical progress should proceed in an exponential manner date back to the theory advanced by Henry Adams [13]. Adams compared the acceleration of progress with the effect of a new mass which is introduced into a system of forces (previously in equilibrium) to accelerate the system's motion until a new equilibrium is established. The accumulated information is analogous to the distance traveled by the new mass; the rate of information gain is analogous to the speed; and the second derivative of information over time is analogous to an acceleration which is assumed constant. Adams further remarks that science is doubling its complexities every ten years, which is equivalent to an exponential model of technological progress.

Hartman derives his model from a simple analogy with reaction processes in a gas [1]. In Hartman's "gas",

the molecules are scientists and pieces of information, both occurring at a given volume density (N scientists per cubic foot). The "scientist molecules" do not move significantly, whereas the "information molecules" move with assumed constant velocity in random directions. A useful reaction, i.e., the generation of new information, is supposed to occur when the scientist molecules have a "reaction cross section" on being hit by the information molecules. The "reaction cross section" is simply the target area of scientists for the generation of new information through collision between the two types of "molecules."

The information gain in this model depends on the amount of information already available and this fact closely parallels the general thinking on the production of scientific and technological results. The author of this model assumes ideal communication between all investigators and all sources of information. He further assumes that every opportunity presented by this communication can in fact be exploited. Both of these assumptions certainly do not hold for the overall growth of science and technology where communication is not ideal and where far more opportunities for the production of new information exist than can be followed up. Consider, for example, the simultaneous discovery of a new theorem by two mathematicians working independently of each other. However, Hartman's model may be a useful approach to research and development in a specific field or within a small research team.

In addition, it is this author's opinion that this model also has the advantage of flexibility with respect to possible refinements. For example, the use of statistical distributions for the factors taken as constant in the simple model.

In another model, Lenz proposes the use of Pearl's formula to describe biological population growth as a function of time in a limited environment [13]. The biological processes investigated by Pearl were the rate of increase of fruit flies within a bottle, the rate of increase of yeast cells in a given environment, and the rate of cell increase in white rats.

Each of Pearl's examples follows the same simple mathematical law, namely,

$$P = \frac{P_o}{1 + a\ \exp(-at)}$$

where P is the population or cell mass at time t, P_o was the population at the beginning of the experiment, and A and a are constants. If this law is applied to the generation of new information the following interesting analogy results:

$$I = \frac{L}{1 + B\ \exp(-bt)}$$

where I is the accumulated information (state of knowledge) at time t, L is the upper limit of information due to some constraint, e.g., an individual's Intelligence Quotient (IQ), and B and b are again constants. The constant B fixes the

position of the curve in the time dimension, i.e., a difference in B means shifting the curve to the right or to the left. The constant b fixes the slope of the curve.

One of the advantages of this biological analogy is explained by the fact that it yields a symmetrical S-shaped curve without any further assumptions concerning the given constraints. Thus, with the knowledge of an ultimate limit, the complete curve can be extrapolated on the basis of a very short time-series. The critical point of this analogy is, of course, to know which scientific, technical, and functional parameters, if any, can be expected to follow this simple law precisely. Prehoda comments that S-shaped curves apply to such diverse situations as the market sales of a new innovation, military build-up in the force of an external threat and tax trends [14].

Another interesting aspect of the biological analogy is that it identifies natural stages of development, which succeed each other in an orderly fashion. That is, from gestation to maturity there are many intervening processes which cannot be eliminated - nor can they be accomplished instantly - regardless of motivations or incentives. The life-cycle analogy, therefore, seems to have a considerable degree of utility as regards the ordering or structuring of events.

However, the analyst must recognize this analogy carries with it the erroneous implication that each technology has a "life" of its own, and that its evolution is governed by some internal dynamic law with stages of fixed length. In

fact the transition from one stage to another may in some cases be so rapid as to be almost unnoticed. It may happen that a technology approaches maturity for a specialized market much faster than it does in other markets. Moreover, change need not always result in progress in the forward direction. Instances of regression have occurred where a technology reverts to an earlier state as a result of developments in other fields. For example, Ayres cites the example of early nineteenth century robots which were allowed to lapse, only to be revived again in the twentieth century [4].

An examination of the models outlined in this section leads to the conclusion that no model has so far succeeded in taking into account more than a limited number of influencing factors by assuming relationships that are generally improved or not known in detail. No explanation has yet been given of why growth trends in technical parameters or functional capabilities should be directly proportional to the growth of accumulated knowledge. They may in fact be proportional to the logarithm of the accumulated knowledge. The principal usefulness of such simple analytical models may be seen to lie in their making visible the influence of external factors which are responsible for the relationship between technical progress and time.

2. Phenomenological Models

An obvious method of technological forecasting is to assume that whatever has happened in the past will continue

to happen in the future, provided, of course, there are no major disturbances. It is natural to let experience be a guide for future expectations and the more inferences are tested based on this past experience and found to "fit the observations," the most subjective confidence can be obtained. This increased confidence can, moreover, be expressed numerically regardless of whether or not there is any generally accepted theory to explain the observed relationship. For example, if it is known that the crime rate has a high correlation with the phases of the moon, this information could provide valuable information to those who are responsible for the scheduling of policemen. Before a numerical expression can be derived certain basic characteristics need to be established. First, the trend under study should be capable of being quantified as a ratio scale. Second, the trend, i.e., the relationship, should have a significant effect in the area being forecast. Third, a data base should exist on which to establish a trend line.

Several types of trend curves which describe a relationship between a parameter and time have been presented by Jantsch [1]. He divides trend curves into five classes which are illustrated by the accompanying sketches and examples.

The first class, linear increase with flattening, is shown in Figure 1. The efficiency of thermal power plants exhibits these characteristics and the mechanization of human work expressed in terms of the decrease in annual working hours per man has also been linear over the past 75 years.

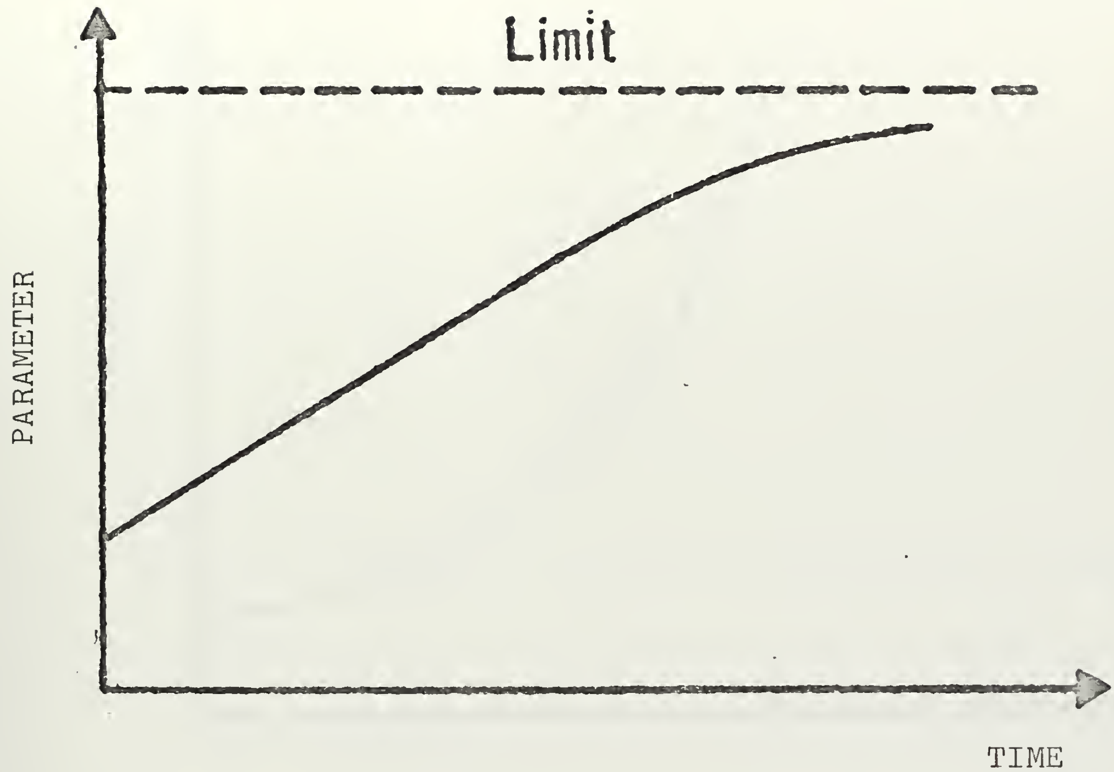

Figure 1. Linear Increase with Flattening.

The second class, exponential increase with no flattening in the considered time range, is shown in Figure 2. These characteristics are exhibited by a number of functional capabilities. For example, the maximum combat aircraft speed or the maximum transport aircraft speed up to the planned operational availability of the SST. The almost precisely exponential increase of energy conversion efficiency (lumens per watt) in illumination technology from the paraffin candle to the gallium arsenide diode seems to suggest that a functional capability can follow a class 2 trend until it abruptly hits a limit - the gallium arsenide diode's efficiency is already close to one.

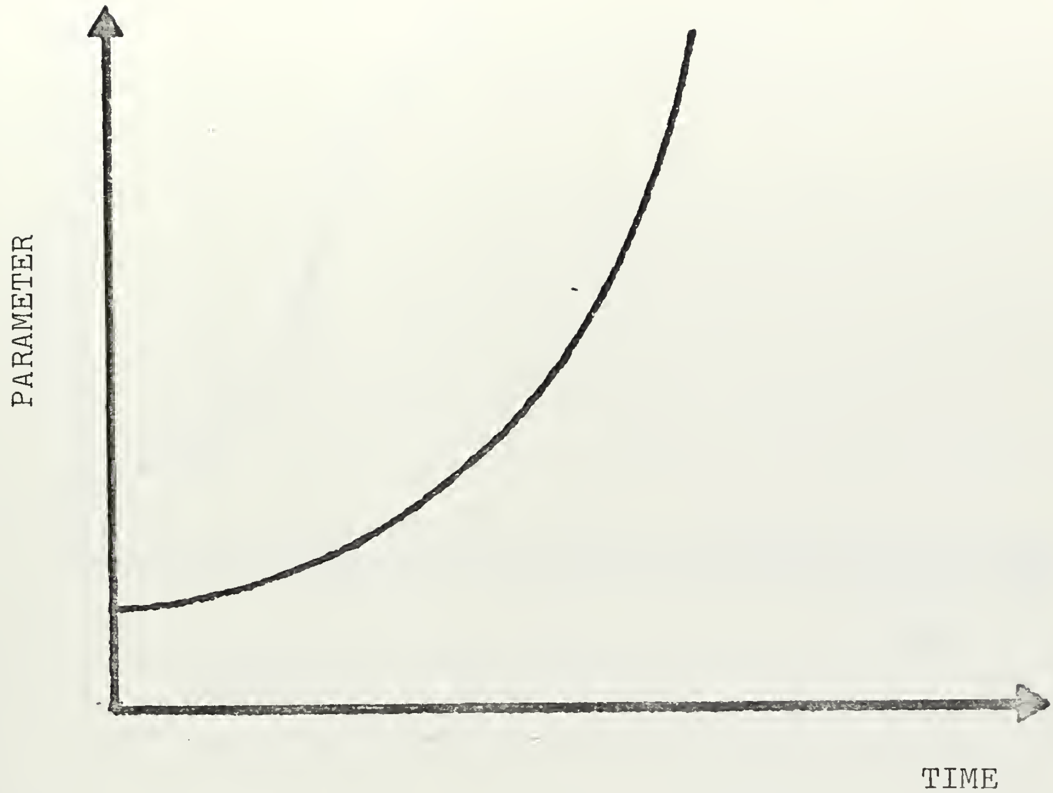

Figure 2. Exponential Increase With no Flattening in the Considered Time Range.

The third class, the S-shaped curve, is shown in Figure 3. Apart from the logistic curves discussed previously, one may also find S-shaped growth curves which can represent Gompertz'law. This law describes growth phenomena in some areas of economics, such as income growth. In contrast to Pearl's law, Gompertz' law represents a non-symmetrical S-curve.

The fourth class, double exponential or steeper increase, with subsequent flattening, is shown in Figure 4. These characteristics hold for some functional capabilities in areas of concentrated research and development. Two examples are maximum speed attained by man and operating energy

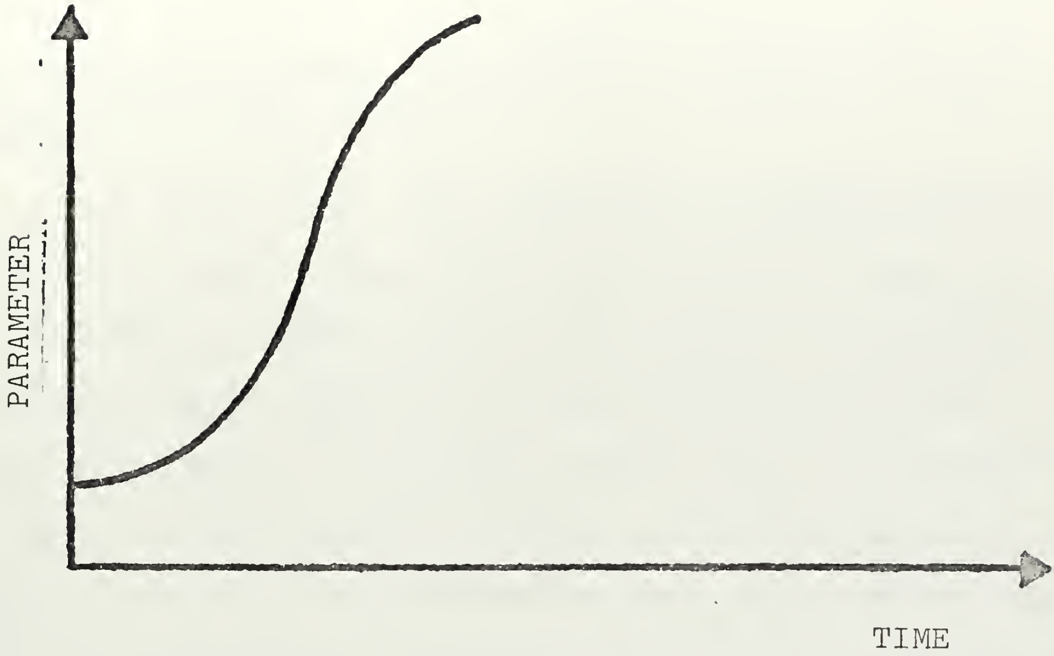

Figure 3. S-Shaped Curve.

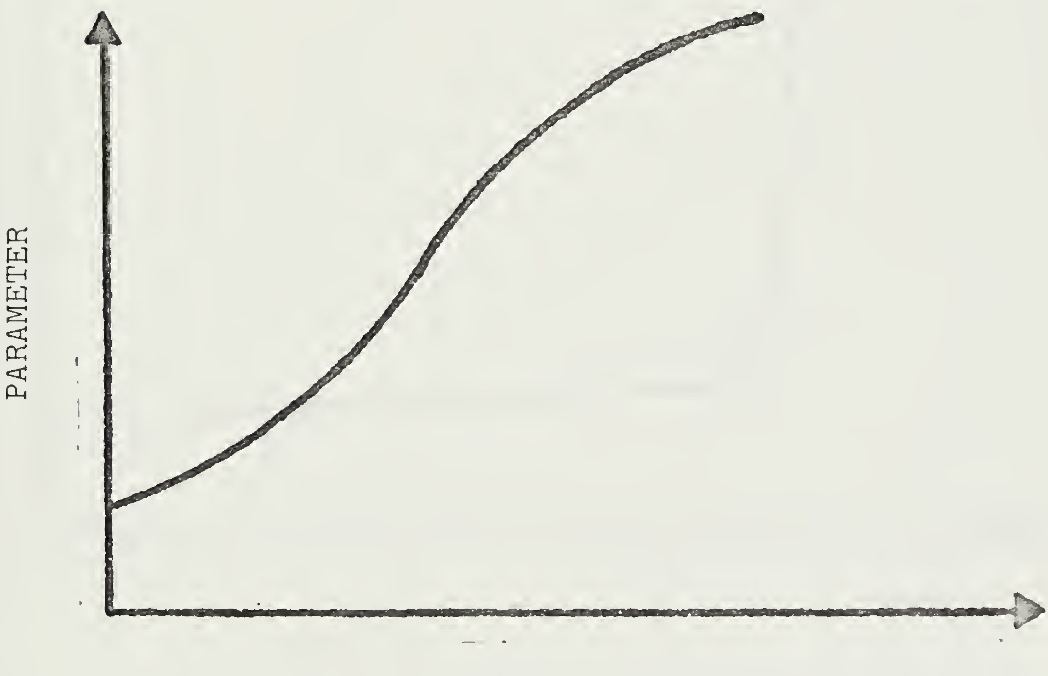

Figure 4. Double Exponential Or Steeper Increase with Sub-Sequent Flattening.

in particle accelerators. It is interesting to note that operating speed of commercial computers would also belong to this class.

The fifth class, slow exponential increase followed by sudden and rapid increase with eventual flattening, is shown in Figure 5. This type of curve applies to the maximum explosive power available for delivery at a distance. The very steep rise is, of course, mainly due to the advent of nuclear fission and fusion weapons. The flattening of the curve is caused by the effective limit of utility at approximately 100 megatons rather than by technical limitations.

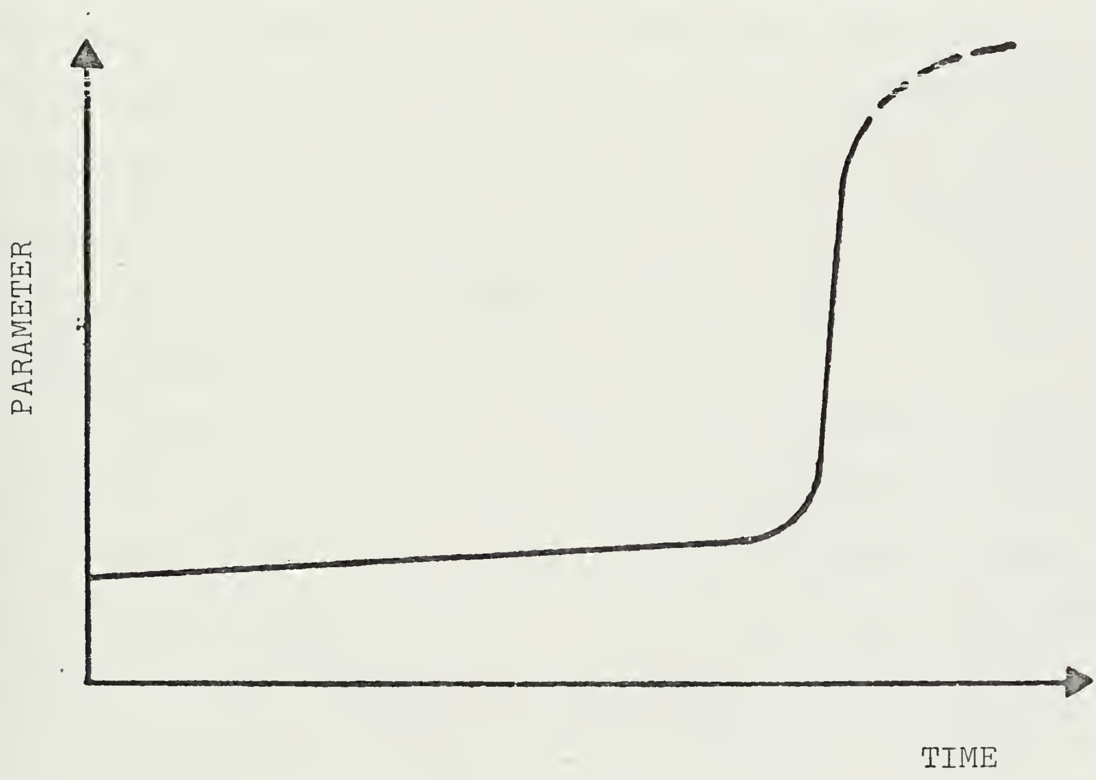

Figure 5. Slow Exponential Increase Followed by Sudden and Rapid Increase with Eventual Flattening.

Trend evaluation and extrapolation on a simple phenomenological basis has become a widely used technique. It provides a first answer to the question of whether a specific goal has a reasonable chance of being attained by the same mechanism which produced past progress. Two refinements of trend extrapolation can be applied with considerable advantage in suitable cases: forecasting by analysis of precursive events, and forecasting by envelope curve extrapolation. They will be discussed in the following paragraphs.

Forecasting by analysis of precursive events uses the correlation of progress trends between two developments, one of which is leading the other. Lenz has stated that if the time lag is sufficiently long, a useful long-range forecast is possible [13]. He gives an interesting and plausible example, as shown in Figure 6, of a sequential relationship in the correlation of the maximum speed of military aircraft to the maximum speed of commercial aircraft.

The two developments are logically related to each other in the way depicted. That is, the research and development effort applied to combat aircraft eventually bears fruit in the transport sector. It should be noted, however, that such a simple correlation is valuable for forecasting only insofar as the leader-follower relationship is maintained. This relationship has undergone several changes in the example cited above. Civilian transport development, for the first time, has recently received substantial support from the government. With the cancellation of the SST program

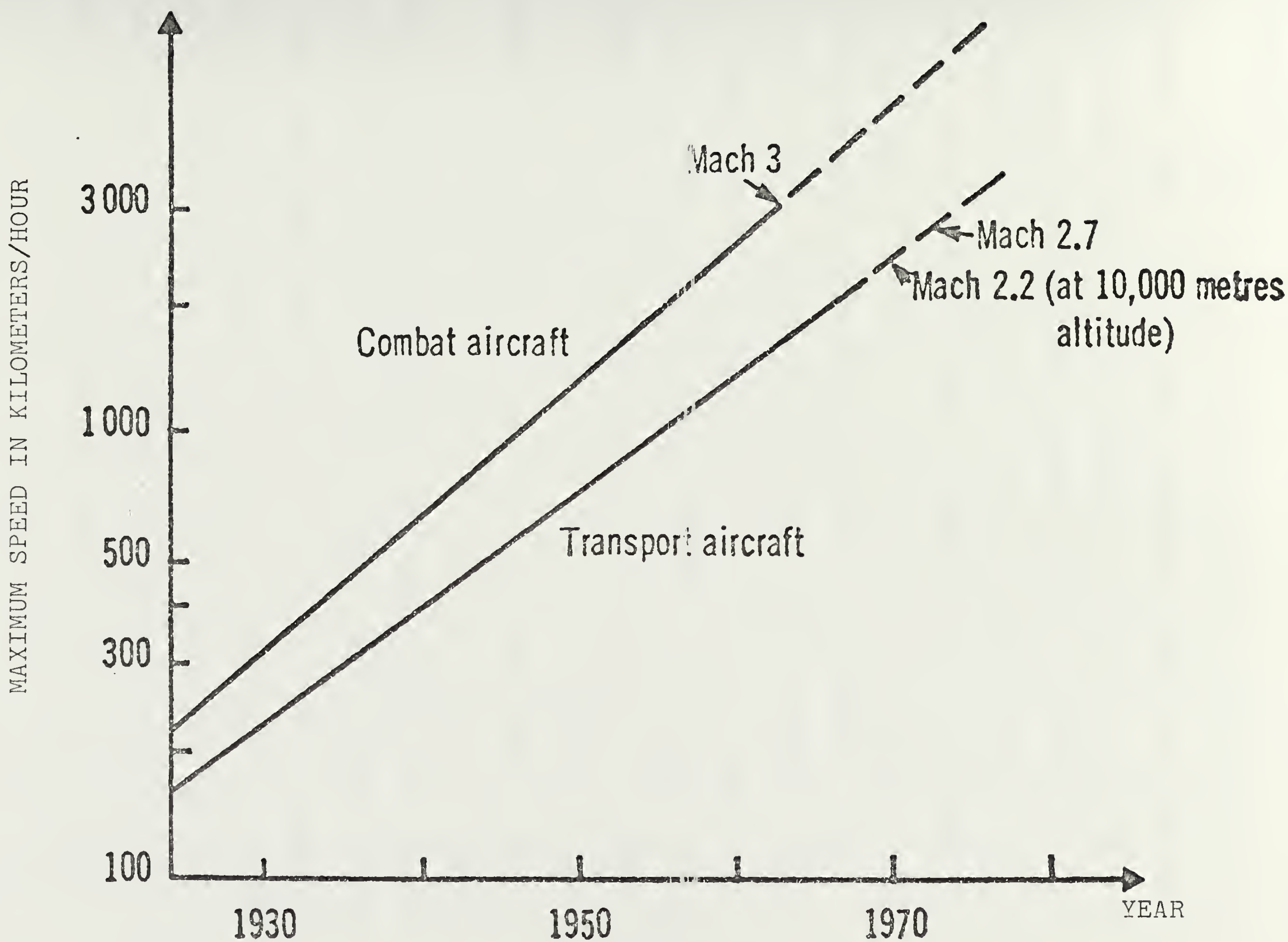

Figure 6. Relationship Between The Speeds of Combat and Transport Aircraft.

and the recent problems in military cost overruns, the trend curves and the correlation between them is a matter of great speculation.

Ayres, who has treated envelope techniques in the greatest depth, states that envelope curves are hypothetical curves that describe the maximum performance available for any particular functional characteristic, regardless of the configuration of the device which is employed [4]. The definition of an envelope curve is best presented by means of an illustration. Figure 7 is a plot of the maximum energy available from high-energy particle accelerators (atom smashers) [2]. Typically, each new type of machine takes the lead for a short period of time and then, because of inherent limitations, it reaches the end of its phase of rapid improvement while a newer invention escalates to a higher level. The "envelope" is a curve which approximates the general trend and is tangent to the individual performance trends.

Envelope curves can be used to enclose the individual S-shapred curves and then to extrapolate a projected range of the capability rather than a single-valued projection. Livingston has stated that envelope curves can yield more reliable forecasts than those approaches based mainly upon consideration of the projected capabilities of specific techniques [2]. The logic involved here is that if the forecaster, say in 1950, looked closely at the capabilities of known techniques for particle accelerators, there limits or barriers would be fairly visible. On the other hand, the

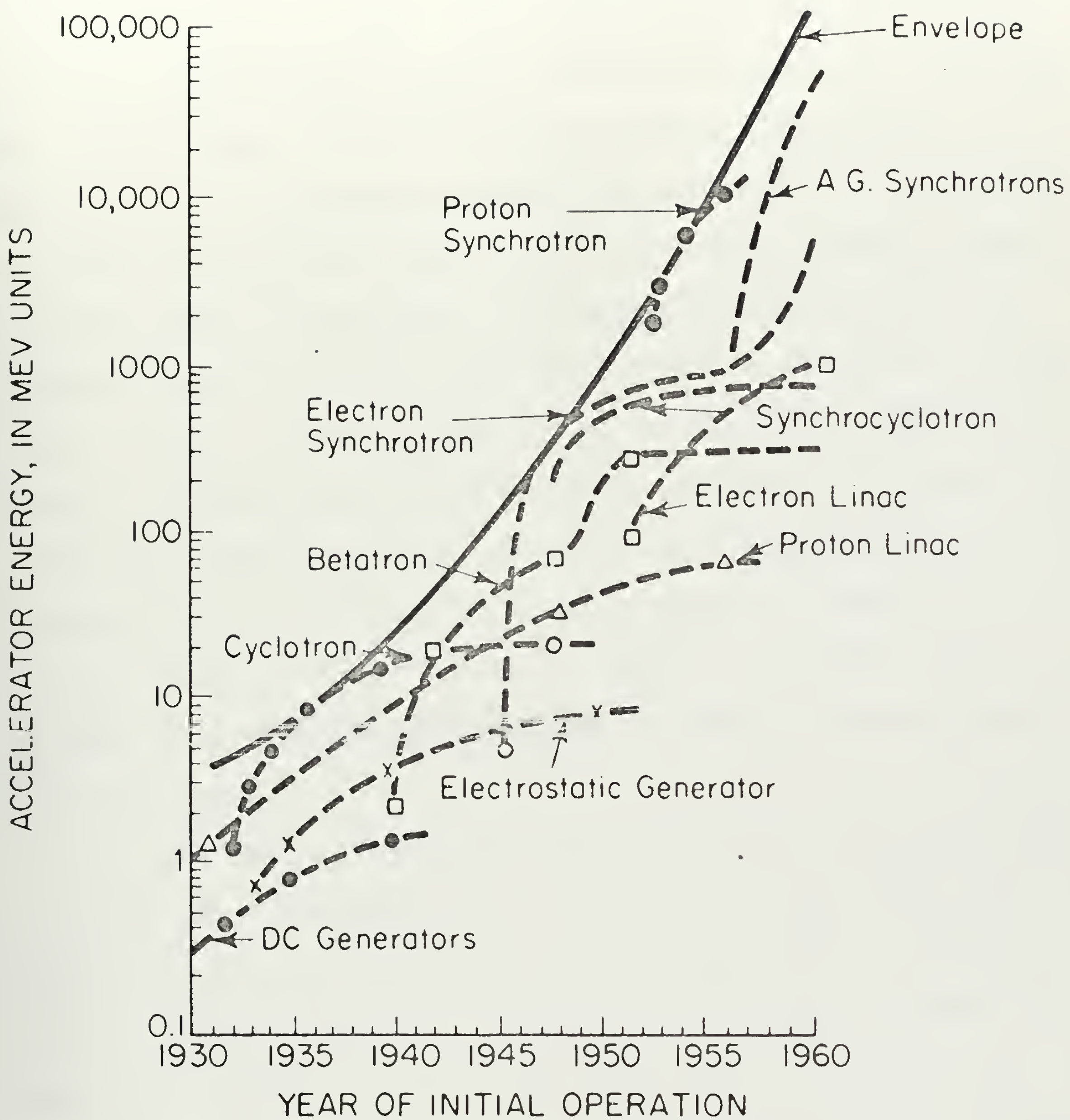

Figure 7. The Rate of Increase of Operating Energy in Particle Accelerators.

future innovations or break throughs would be more difficult, if not impossible to see. The result would, most likely, be an overly conservative forecast showing an incorrect leveling off. In envelope extrapolation the burden of proof is shifted and the forecaster assumes that progress will continue within the envelope range unless a definite limit or perturbation can be identified. He asks what might cause the continuation of invention, not what detailed hardware or technique will be required (engineering development). The technique of envelope-curve extrapolation presents an interesting proposition which can cause forecasters to change their approach to the analysis of a forecast area. It leads to a broader viewpoint that forces an analysis of limits and at the same time promotes an analysis of causal factors acting upon the system.

The final technique to be discussed in this section is mathematical trend-fitting. These techniques have been developed with the use of well known statistical techniques and are widely employed in economic forecasting. Trend fitting can be simplified by determining first to which class a given trend belongs: linear increase; exponential increase or S-curve. If the empirical data to be used in making the projections are from a reliable source, the appropriate equations from the first step may be used in conjunction with the method of least squares to project future values of significant parameters.

The method of least squares fits a straight line, parabola, or higher degree polynomial to a given set of data.

It specifies that the best fit for a polynomial of a given degree results when R, the sum of the squares of the residuals, is a minimum. It is assumed that the values of the independent variable X_i, are error free. The residuals are defined as the distances between observed values of the dependent variable Y_i, and the corresponding y values of the curve being fitted, measured parallel to the y-axis.

To determine the parameters (constants) of the desired polynomial a set of normal equations is derived by a squaring and minimizing process. For example, if f(x) is a straight line, y = a + bx. The ordinates of the straight line being fitted are a + bx. The summation becomes:

$$R = \sum_{i=1}^{n} [Y_i - (a + bX_i)]^2$$

where n is equal to the number of data points.

The most common method of trend prediction makes use of regression analysis. If two parameters X and Y are to be related to each other, one postulates a relationship between them, for example y = a+bx, and minimizes the total error for a number n of observed pairs (X_i, Y_i) by the least squares method.

By setting the first derivative of R equal to zero, one gets the necessary condition for the minimum. Solving for the least squares estimator of the slope yields:

$$b = \frac{\Sigma XY - \frac{\Sigma X \, \Sigma Y}{n}}{\Sigma X^2 - \frac{(\Sigma X)^2}{n}}$$

Once the estimated slope, b, is known, the estimated intercept, a, is easy to compute:

$$a = \bar{y} - b\bar{x} = \frac{\Sigma Y}{n} - b \frac{\Sigma X}{n} .$$

Extrapolation of time series using phenomenological models is likely to be the best method of forecasting whenever most of the data is historical and exhibits definite trends in its development. In general, the startling and unexpected will not be forecast. Because it is analytical, trend extrapolation keeps the role of the forecaster's bias at a minimum. Attempts have been made to eliminate all forecaster bias by deriving mathematical expressions for the growth of technology (see Section 1). While it is true that the growth can often be represented by an analytic model, as yet no particular successful analysis has taken place. The situation is far too complex to be modelled successfully with present-day technology. Thus, in practice forecasting still proceeds with the trend extrapolated manually.

C. MORPHOLOGICAL ANALYSIS

Trend extrapolation and contextual mapping generate new, though more or less inaccurate, information about specific functional capabilities or parameters or simple parameter combinations. They do not yield any information about the nature of functional technological systems. The morphological method, on the other hand, was developed by Zwicky for identifying, indexing, counting, and parametrizing the collection of all possible devices to achieve a specified functional capability [4].

In his own words Zwicky states that: "The morphological approach to discovery invention, research and construction has been conceived and developed for the purpose of dealing with all situations in life more reasonably and more effectively than hitherto. This is achieved through the study of all relevant interrelations among objects, phenomena and concepts by means of methods which are based on the utmost detachment from prejudice and carefully refrain from all preevaluations." In other words, technology is considered as a system with various components. Each component is considered in all its ramifications and then all permutations are considered. As a result a set of "inventions on paper" are derived which may be considered as possible results of the technology. This approach provides a method of systematically exploring all available opportunities.

Perhaps the obvious application of this technique is in the analysis of technological opportunities. Apart from the chance of using the scheme to anticipate actual inventions, there is at least a possibility of parametrically characterizing the optimum configuration for a particular mission or task.

Again, to quote Zwicky [1]: "There are, in particular three types of generic problems which the morphological analysis attempts to solve. These are:

How much information about a certain limited set of phenomena can be obtained with the help of a given class of devices? Or, stated differently, what devices are necessary

to obtain all of the information about a given set of phenomena?

What is the sequence of all effects issuing from a certain cause?

Deduce all of the devices of a given class, or all of the methods of a given class or, generally speaking, all of the solutions of a given definite problem."

An answer to the second question is found in the relevance tree technique, which will be discussed in section four. The third problem is the crucial one for exploratory forecasting and will therefore be discussed here in greater detail.

Jantsch summarizes the step-wise solutions to a generic problem of the third type as follows [1]:

First, an exact statement is made of the problem that is to be solved. For instance, one may wish to study the morphological character of all modes of motion, or of all possible propulsive power plants, telescopes, pumps, detection devices, and so on. If one specific device, method, or system is asked for, the method immediately generalizes the inquiry to all possible devices, methods or systems which provide the answer to a more generalized request. The task of formulating the initial statement or definition of the problem on hand is exacting. Zwicky affirms that "one is hard put to find in the existing literature satisfactory definitions of well-known devices like telescopes, pumps, and so on.

Second, the exact statement of the problem to be solved, or the precise definition of the class of subsystems or components to be studied, will reveal automatically the important characteristic parameters on which the solution of the problem depends. For instance, in the case of telescopes, some of these parameters are the location of the telescope (medium in which it is embedded), the nature of the aperture (A) and the recording device (R), the nature of the changes to which the light is subjected from A to R, the motion of the telescope, the sequence of operations, etc. The second step thus involves the study of all these significant parameters.

Third, each parameter P_i will be found to possess a number of K_i different independent irreducible values P_i^1, $B_i^2, \ldots, P_i^k$. For example, the parameter "motion" of a telescope may have the independent values P^1, P^2, P^3 = translation in three directions; P^4, P^5, P^6 = rotary motion; etc. These matrices are written in the following scheme:

$$\begin{matrix} \left[P_1^1, \ P_1^2, \ \ldots, \ P_1^{k_1} \right] \\ \left[P_2^1, \ P_2^2, \ \ldots, \ P_2^{k_2} \right] \\ \cdots\cdots\cdots\cdots \\ \cdots\cdots\cdots\cdots \\ \left[P_n^1, \ P_n^2, \ \ldots, \ P_n^{k_n} \right] \end{matrix}$$

If one element is encircled in each matrix and all the circles are connected, every resulting chain of circles represents one possible solution of the original problem.

It is exceedingly essential that up to this point no question be asked as to what value one or the other solution may have. Such premature curiosity almost always defeats the unbiased application of the morphological method. However, once all of the solutions are found, one must know their relation to any given set of adopted performance values.

The fourth step in the morphological analysis is the determination of the performance values of all of the derived solutions. The performance evaluation must be carried out on a universal basis if one wishes to avoid getting lost in an enormous confusion of details. This is not always an easy task.

The fifth and final step involves the choice of particularly desirable special solutions and their realization. The conviction that all solutions can be realized, independent of time, is inherent in morphological thought. Since time is not considered, morphological analysis is not a forecast per se, but it is a useful organizing tool, a source of insights and a starting point for further analysis.

The basic method and its variations can best be explained in terms of a specific illustration. Figure 8, which utilizes the matrix structure discussed under point 3 above, comes from Zwicky himself. He focused attention in great detail on the totality of all jet engines operating in a pure medium (vacuum, air, water, earth) containing simple elements and being activated by chemical energy.

There are 36,864 combinations of the above pure-medium jet engines containing simple elements only and being activated

$$[\,p_1^1,\ p_1^2\,] = \text{intrinsic or extrinsic chemically active mass}$$

$$[\,p_2^1,\ p_2^2\,] = \text{internal or external thrust generation}$$

$$[\,p_3^1,\ p_3^2,\ p_3^3\,] = \text{intrinsic, extrinsic, and zero thrust augmentation}$$

$$[\,p_4^1,\ p_4^2\,] = \text{internal, external thrust augmentation}$$

$$[\,p_5^1,\ p_5^2\,] = \text{positive and negative jets}$$

$$[\,p_6^1,\ p_6^2,\ p_6^3,\ p_6^4\,] = \text{nature of the conversion of the chemical energy into mechanical energy}$$

$$[\,p_7^1,\ p_7^2,\ p_7^3,\ p_7^4\,] = \text{vacuum, air, water, earth}$$

$$[\,p_8^1,\ p_8^2,\ p_8^3,\ p_8^4\,] = \text{translatory, rotatory, oscillatory, and no motion}$$

$$[\,p_9^1,\ p_9^2,\ p_9^3\,] = \text{gaseous, liquid, solid state of propellant}$$

$$[\,p_{10}^1,\ p_{10}^2\,] = \text{continuous and intermittent operation}$$

$$[\,p_{11}^1,\ p_{11}^2\,] = \text{self-igniting and not self-igniting propellants}$$

Figure 8. Morphological Analysis of Jet Engines.

by chemical energy. However, there are some technical restrictions which reduces the number of possible jet engines to 25,344. For example, the distinction in Figure 8 between internal and external is meaningless for the case of zero thrust augmentation. Obviously many of these permutations have never been tried out or even thought about, i.e., they have not been "invented" yet. Even if we disregard jets designed to operate in water or in the earth (hydrojets and terrajets), there remain more than 10,000 possible configurations of which only a small number have ever been given serious attention.

The example marked in the matrix above by circling specific parameters is the interplanetary aeroduct or ramjet. Zwicky remarks, that "the principal point of interest is the presence of the element P^2, in the above matrix. It means that the chemical energy is derived entirely from the surrounding medium and that the jet engine operates although it does not carry any propellants with it at all." One way to achieve this characteristic is to make use of the sun's energy which is stored in the upper atmosphere in the form of excited and ionized atoms and molecules. The inclusion of a jet which conceivably might use this stored energy would stimulate research, to find out about the nature and number of the excited particles and research in the possibilities of de-exciting the particles and using the energy gained in aeroducts, aeropulses, and other devices for the generation of propulsive power. It is believed that such gradual and

and continuous acceleration might ultimately prove to be superior to the use of nuclear propulsion for space ships leaving the earth.

The practical application of the morphological method is conceivable over a wide spectrum. It allows forecaster's to see important interactions between various branches of science, such as physics, chemistry, biology, etc. Frequently a modest advance in one discipline may have a dynamic impact on a seemingly unrelated branch of science. The basic attitude of this technique can certainly be found in many forms of technological planning. The full-size application of this technique as it has been practiced by Zwicky, has had considerable success in rocket and jet fuel development. He also derived the possibilities of making the moon habitable and even went so far as to investigate the possibility of changing planetary orbits to make them habitable.

D. SCENARIO WRITING

The term "scenario writing" denotes a technique which attempts to set up a logical sequence of events in order to show how, starting from the present, a future state might evolve step by step. The purpose of a scenario is <u>not</u> to predict the future. It refines information on the forseeable "climate" for various branches of science rather than outlining probable technological achievements. Prehoda states that many of the best science fiction stories are based on refined scenarios, and some science fiction authors have been good technological forecasters, e.g., Jules Verne [14].

Perhaps the most authoritative discussion of the purposes and values of scenario writing may be found in the writings of Herman Kahn [15]. Kahn cites two advantages worth noting: First, scenarios are an effective tool to force the analyst to plunge into the unfamiliar and rapidly changing world by dramatizing and illustrating the possibilities they focus on. Second, scenarios are an antidote for concentrating exclusively on the forest and ignoring the trees. They force the analyst to deal with details and dynamics which he might easily avoid treating if he restricted himself to abstract considerations. Typically, no particular set of the many possible sets of details and dynamics seems specially worth treating, so none are treated, even though a detailed investigation of even a few arbitrarily chosen cases can be most helpful.

Kahn himself warns of the dangers that may arise from the use of scenarios to guide and facilitate further thinking and analysis. Specifically, the initial conjectures might erroneously be assumed to be sufficiently correct to lead to scenarios with some content of "reality." However, as Kahn remarks, "a specific estimate, conjecture, or content, even if it is later shown to have serious defects, is often better than a deliberate blank which tends to stop thought and research."

An interesting version of scenario-writing, combined with cost/effectiveness analysis has been given by Ayres in the food production area [16]. Essentially it attempts a critical evaluation of the fundamental alternatives (such as non-photosynthetic energy sources) on economic grounds and

in broad contexts - resulting in the rejections of some much discussed, technically feasible solutions. He points out that this approach merits particular attention in the area of "social engineering."

Scenario-writing is also applied by several of the big oil companies which are deeply interested in future economic political, and social environments [1]. It is also applied by Honeywell to determine and assess higher-level goals and missions for their PATTERN scheme. PATTERN will be discussed in the following section.

A variation of scenario writing - but having the aim of simulating "reality" is iteration through synopsis. This method consists of writing scenario's in six different fields (demography, psychology, sociology, technology, politics, and economics) and subsequently combining them. The individual scenarios, especially the economic one, could be partially derived by more rigid techniques such as econometric or statistical analysis.

In the Department of Defense the study of future potential threats by scenario-writing is a major activity involving annual expenditures in the millions of dollars [4]. Similar scenario studies are carried out by NATO and other agencies. Although consideration of the potential impact of technological break throughs on the future military - political - social environment, via scenario-writing, is not currently a major component of the above mentioned activities, it has shown tremendous potential for future forecasting exercises[4].

E. UNCERTAINTY TECHNIQUES

Technological forecasting is, by definition, an area deeply concerned with uncertainty. However, too often the forecasts that are presented to decision makers fail to include an explicit description of the inherent uncertainties. Three techniques developed by Research Analysis Corporation are described that can be used to convey such information to decision makers [2]. They are based on probability theory and permit the construction of probability distributions of total projects from the distribution of individual parameters.

The basic assumption of each of these techniques is that forecasting inputs such as growth rates and R&D costs can be considered to be random variables which have probability distributions. The techniques then combine these distributions in accordance with the equations of the particular forecasting model to produce probability distributions instead of single point estimates for demand and/or capability projections. The techniques, which differ only in method of combination of distributions, are enumerated and briefly described below.

The first technique derives the moments of the distribution curve. The moments are a set of mathematical properties which are capable of completely defining a particular distribution [1]. Moreover, these can be combined by certain mathematical formulae to produce corresponding moments for any combination of sums and products of curves. This technique can be used to convert user-specified parameters to the

moments of their distributions; combine these moments in the manner specified by the forecasting model; and reconvert this combination of moments to the distribution it describes.

The second method is the Monte Carlo technique. In this method, many iterations of the same forecasting model are run, each of which changes the inputs of the model in accordance with random values drawn from the probability distributions of the inputs. After a number of such iterations, a frequency curve can be developed for the model's outputs.

The third and final technique is called symmetric approximation. This method employs the same basic approach as the derivation of moments technique, but utilizes certain approximating relationships to determine the moments of the distributions. To date, tests at Research Analysis Corporation have been run utilizing Beta distributions. This is a type of distribution which, in its symmetric form, resembles a bounded normal distribution. However, it differs from the normal in that it can reflect skewness or flatness - traits which often prove valuable for expressing uncertainty.

For all three techniques the user must select a most-likely value (presumably this would correspond to the input that the user would specify if producing only a single point projection), the high value, and the low value. In addition, the user selects a type of distribution from a fixed set of distributions which can be described qualitatively in terms of skewness and variance. With these user-specified parameters as inputs, each technique can produce probability distributions for the projections which result

from the particular forecasting models. An example will help to illustrate the way these techniques can be employed by a firm for technological forecasting.

Suppose a manager is interested in estimating the costs of a missile airframe. The missile is not yet designed or built, so no production-cost data are available. The cost group has placed the airframe cost at $32,000, but the design group has warned that additional sophistication might raise costs above this prediction, and that improvements in some manufacturing techniques hold the promise of lower costs. Calculations provide estimates as low as $26,000 and as high as $45,000. Each of these calculations is based on a set of assumptions concerning labor and overhead rates, material costs in the future, and design details which are not yet firm and are subject to some uncertainty. After considering each factor, the analyst enters his final estimate as $36,000. Obviously, with a single-point estimate the analyst is not telling the hypothetical decision-maker all he needs to know to make a rational decision.

If the reasoning that fixed the relevant range of costs at $26,000 to $45,000 could yield information on the probabilities of occurence, the techniques described above could develop the missing information. From this information, a probability distribution for costs of the airframe could be developed. When combined with similarly determined distributions of other cost components, total missile cost could be obtained, or even total system cost if other equipment is to

be costed. The techniques would produce statistical measures of the distribution of total cost, including the mean and variance. It would also provide a graphical display of the total cost range implied by the uncertainties associated with the input parameters.

Caution is necessary in using these techniques. Two assumptions are made that may not be valid in every situation. The first is that the user can, in fact, specify a distribution type and the required parameters of that distribution. This assumption highlights the twofold nature of the problem the decision-maker faces. He must first obtain the inputs required for the specification of the distribution and then he must process the distribution into a form which is useful to the decision-maker. The second assumption is that the input variables are independent or that their dependence can be made explicit. Research in this latter area has produced a number of ways of determining such explicit relationships but has not eliminated this constraint altogether [2].

F. COST/BENEFIT ANALYSIS

Cost/benefit analysis does not add any new information to technological forecasting. However, it is used to translate estimates resulting from technological forecasting into economic terms. Cost/benefit analysis in the context of technological forecasting is thus a special technique for binding together a vertical and a horizontal forecast to form an integral forecast. This process makes possible an integral view for decision-making by placing the vertical and horizontal effort on the same basis.

The vertical forecast, usually attempted at the advanced development stage and again at the engineering stage, provides estimates on the development time and costs, production and operating costs and other operational characteristics. The horizontal forecast provides estimates on sales and profits as a function of time. Risk factors may also be estimated for both the vertical forecast (technical risk) and the horizontal forecast (commercial risk). As one might expect, the combination of the two forecasts gives cost flows as a function of time.

In industry there are several performance indices of which the most widely used in "return on capital investment" [1]. This is not, however, a uniquely defined concept, since there are a number of different methods of measuring return. This approach does not consider time explicitly and the effect of interest gained or lost over time. Although it neglects this very foundation of business thinking, it is widely used on the assumption that the time factor can be taken into account in an indirect way.

Costs are, of course, fairly well defined and straight forward in many instances, but not so benefits. In the case of private industry it is only necessary to consider benefits to the corporation, although in some cases a very broad view may be taken as to what constitutes a benefit. Regarding public investments, on the other hand, it is necessary to identify all the beneficiaries, as well as those who may be injured. In too many instances benefits are computed on the

basis of considering only a fraction of the effects on part of the population, and ignoring the rest. For example, it is standard practice for highway departments to compute the benefits from highways only for road users, totally disregarding the hidden "negative benefits" affecting other segments of the economy.

One of the best means of accounting for the time factor in cost/benefit analysis is the method of calculating the present value of a future income stream. The question, in another form, is: What should one assume for the effective forward discount rate r? In words, the discount rate is essentially the expected rate of appreciation of alternative investments currently available. The present value of a future benefit is the amount of money which, invested at r percent per annum, would ultimately produce a yield equal to the projected benefit. In the case of very long-term projects, such as reservoir's and dams, whose benefits must be computed over a time horizon extending 50 to 100 years into the future, it is easy to see that the calculated benefit is extremely sensitive to the discount rate: the lower the rate, the greater the benefit.

The basic expression of the "continuous" approach is the present net value P' of each incremental cash flow C(t) at time t' (counted from t=0 for the present):

$$P' = C(t')\, e^{-rt'}\, dt.$$

Integration over time yields the net present value of the project:

$$P(r) = \int_{0}^{\infty} C(t)\, e^{-rt}\, dt$$

where C(t) is the cash flow (or income) per unit time at future time t. In general, C(t) is negative for the first few years after the initial decision to invest in a new project with positive contributions corresponding to profits coming later on. Because of the rapidly decreasing exponential factor e^{-rt}, a project with a large but long-delayed payoff may have a present worth much less than one whose return is smaller but earlier. The above equation for P(r) can be set to zero, so that it holds for break-even conditions and solved for r, which then represents the inherent rates of return of a project. One could then compare the inherent r with the given limiting r which gives a clearer ranking order from high values of r down to the limiting value of r. One may also decide the maximum amount of research possible if funds have to be raised at different discount rates. It should be noted, however, that there are well-known difficulties associated with this approach. A detailed discussion of this subject can be found in Quirin's text [17].

Ayres cites an interesting example of cost/benefit analysis [4]. The field of water-resources development has been characterized by very long time horizons and low discount rates, with little or no consideration of the impact of technological change on the assumed benefits. For instance, it is clear that if the anticipated benefits of a multipurpose dam assume a requirement for irrigation water,

the cost/benefit calculation should, among other things, include an explicit evaluation of the potential impact of new technologies for water conservation. At first glance this may involve some excursions into rather remote areas, such as the development by American Oil Co. of a technique for "waterproofing" cropland from beneath by injecting a layer of asphalt at a depth of several feet below the surface. This prevents subsurface runoff and increases the water supply available to plants. One of the obvious results of this procedure is to correspondingly reduce the demand for irrigation water, which in turn influences the decisions concerning the size of the dam.

Looking further into the future, cost/benefit analysis may also be expected to become very valuable for the integration of vertical and horizontal forecasts at higher levels, i.e., of environments, social systems or even society. The prerequisite for its use is the quantification of forecasts at these higher levels in economic terms (numeraire). The author believes that attempts to introduce cost/effectiveness analysis, which has success in military administration, into other parts of the Government is a significant step in this direction.

G. OPERATIONAL MODELS

Abt Associates define models as representations of processes describing in simplified form some aspects of the real world [1]. They are the mechanisms by which predictions of the performance of a process or system can be made. Generally

the analyst attempts to duplicate in some kind of model the behavior of the parameters, subsystem, or system with which he is working. Once he has achieved this relationship between the real world situation and his model, he can manipulate the model to study the characteristics in which he is interested.

Models provide some of the most effective means for predicting performance. It is hard to conceive of a prediction system which is not in some sense a model. To construct a model of a real process or system, careful consideration of just which elements need to be abstracted is required. This in itself is usually a worthwhile activity, for it develops insights into the problem.

The purpose in constructing a model of a given situation is to single out certain elements as being relevant to the problem under consideration, to make explicit certain functional relationships among these elements, and to formulate hypotheses regarding the nature of these relationships. These functional relationships enable the analyst to express the model in mathematical form. In this way he is able to determine the most appropriate action to take in the face of a given situation.

The advantage of employing a model lies in forcing the analyst to make explicit what elements of a situation he is taking into consideration and in imposing upon him the discipline of clarifying the concepts he is using. It should

be noted that in this connection the use of numerical parameters, and thus of a mathematical model, is simply a device for conceptual clarification.

A type of model which should prove of special importance in the area of technological forecasting is the simulation model. Abt Associates define simulation as the operation of a model by manipulations of its elements by a computer, a human player, or both. Here instead of formulating hypotheses and predictions directly about the real world, it is possible to make such statements about the properties of the model. Any results obtained from an analysis of the model, to the extent that it truly simulates the real world, can then later be translated back into corresponding statements about "reality."

Among the simulation models are a number of different varieties. There are paper-and-pencil models, usually involving sets of mathematical equations. These can be analyzed by standard techniques, or, if their complexity precludes this, their implications can be explored with electronic computers for any number of input parameter values. Then there are physical simulation models such as might be used in the study of urban development. Here the projected stages of transformation of a city may be displayed with the aid of a miniature mock-up.

A particularly useful kind of physical simulation is that of operational gaming. It involves role-playing by

human subjects in a laboratory situation in which the participants simulate real world decision-makers in a conflict of interest setting.

Gaming has been used in forecasting the possible impact of new or future technologies and it has been used for some time in this connection by military administrations, mainly for studying the implications for the future of combinations of specific technological and strategic concepts, from the viewpoint of both one's own forces and those of the enemy [1]. With forecasting assuming ever-increasing importance, gaming, using appropriate constraints on the moves of both players, may become a valuable technique for the evaluation of alternative technological developments. Gaming can be extended to study complex problems facing society and is becoming recognized as one of the potentially most suitable techniques for "social engineering" [18].

H. INPUT/OUTPUT ANALYSIS

Leontief has high hopes that input/output analysis might become useful for technological forecasting [19]. Originally the interest in the application of input/output analysis to forecasting was stimulated by the hope of improving the forecasting of the two common relationships between input and output; (a) the "production function," expressing the output in terms of major inputs, such as labor and capital; (b) the trend of labor productivity ratio over time.

The dynamic use of input/output analysis has become the principal object of study by Almon [20]. He has built a

computer model for an inter-industry forecast up to 1975. Forecasting the United States economy from input/output tables is restricted to "hindsight" as long as the preparation of the tables lags behind in time. However, input/output analysis has already become a valuable technique for use in connection with manpower and unemployment problems [1].

A Rand Corporation study for the Air Force, on the basis of input/output analysis, attempted to forecast the creation of new industries in the aerospace industry [1]. Arthur D. Little, Inc. applied input/output analysis to the identification of suitable research and development programs in the field of oceanography [1].

One may expect that such analysis will be recognized as a valuable means of studying structural changes in a clear and explicit manner. General trends - such as the increase in volume of activity for the services, the invasion of one industrial sector by another, the changes in the supply and demand of raw materials, and many others - can be followed explicitly.

The attractive feature, therefore, of the input/output approach is that irregularities in the trend curves show up explicitly, often in terms of readily identifiable causes such as "bottlenecks" in the number of servicemen or of essential experimental facilities in a new field. For example, superconductivity cannot be investigated on any reasonable scale without a helium liquifier for the laboratory [4].

The unattractive feature is simply that in many cases the amount of quantitative methods required is too great in relation to the conclusions one can reasonably expect to arrive at [4] . The cumulative uncertainities due to combining and manipulating a large number of equations and proportionality constants, each one of which is likely to be individually imprecise, must be such as to make the net result often little better than a guess.

At the present state of the art it is the author's opinion that it is difficult to consider input/output analysis seriously as a long-range forecasting tool. Ayres points out, however, that it may be extremely useful as a teaching device for analysts and decision-makers and as such is a worthwhile contribution to the general discussion of exploratory forecasting techniques [4].

IV. NORMATIVE FORECASTING TECHNIQUES

A. INTRODUCTION

Exploratory technological forecasting as stated previously starts from today's basis of knowledge and is oriented towards the future. Normative technological forecasting, on the other hand, first assesses future goals, needs, desires and missions and works backward to the present to see what capabilities now exist or could be extrapolated to meet future goals [1]. Bright cites the Navy's "Polaris" Program and NASA's "Man on the Moon" Program as two good examples of "needs-oriented" normative forecasting [2].

Jantsch states that normative technological forecasting is meaningful only if two conditions prevail [1]. First, normative forecasting is applicable only in a "closed" society. That is, if the levels to which it is applied are characterized by constraints, then normative forecasting can be applied only if the needs or missions are "closed" by natural or artificial forces or by consensus. For example, they could be "closed" by an agreed set of values or ethical directives. Second, normative forecasting depends on an abundance of opportunities. That is, if more opportunities exist and are recognized on these levels than can be exploited under the given constraints, then normative forecasting can be applied and is essentially an attempt to select an optimum among the recognized opportunities.

The author believes the first of the two conditions for normative forecasting - a "closed" system - will be less

readily accepted by a democratic society unless the program is well-defined. The basic difficulty with a "closed" system within a democratic society is the problem of general consensus. Brooks points to the necessity for widespread consensus in areas where individual interests are involved [5]. For example, consider urban transportation and pollution control in contrast to the space program, where few people have to be convinced in spite of the large public expenditure involved.

The search condition - an abundance of opportunities - is, in the author's opinion, the situation as it exists today. To illustrate this point reference is made to the results of a study conducted by the National Planning Association [1]. If the United States undertook to achieve all its present national goals, it would cost fifty per cent more than the total Gross National Product in this period. The abundance of opportunities is further emphasized in a McGraw-Hill survey of research and development in United States industry in which only twenty four per cent of a complete cross section of industry indicated "lack of profitable projects" as the major obstacle to the performance of more research and development [1].

A survey of the literature on normative forecasting techniques indicates that most techniques bear a strong relationship to the methods employed in operations research/ system analysis. Since many practitioners consider each to be a subset of the other, the author will not attempt to

differentiate between the two. However, it is worth noting that the operations research/systems analysis framework is designed to aid decision-makers in choosing a course of action by investigating his full "problem" and that technological forecasting in this sense is but a part of this overall "problem." The Rand report edited by Quade is recommended as an excellent treatment of the contrasts and similarities of operations research and systems analysis [21].

The subject matter of operations research/systems analysis is indeed vast and includes a large number of areas not explicitly relevant to technological forecasting. However, techniques such as mathematical programming, decision matrices, network analysis, and relevance or decision-trees have found practical use in normative forecasting. This section includes a description, possible application, and a critique of these techniques.

It is important to note that scenario writing, uncertainty techniques, cost/benefit analysis, operational models, and input/output analysis, which have been discussed in Section III, are also techniques from the field of operations research/systems analysis. Although these techniques are discussed in the opportunity-oriented framework of exploratory forecasting, the author believes such techniques are useful in the mission-oriented sense of normative forecasting and that perhaps a combination of the two techniques is best.

B. MATHEMATICAL PROGRAMMING

A method of solving the problem of optimization of project selection is to maximize the total net value of projects under a budget constraint. This reasoning has intuitive appeal since planned activities undertaken to achieve an objective usually depend on decisions which are influenced by cost. The most common form of models using operations research/systems analysis techniques is thus found to be a combination of economic analysis, chiefly to determine the present net value of projects from estimated characteristics, and operations research/systems analysis techniques.

Mathematical programming techniques as described in Jantsch's text have been applied in several models [1]. For example, Asher has developed a linear programming model for a pharmaceutical company. The variables used in the model include possible research projects, value of success, cost per man-hour, available man-hours, and available chemicals. The ranking criterion is the maximum expected net value, taking into account availability of man-hours and chemicals.

One of the most ambitious mathematical programming models to date is Program Analysis for Resource Management (PARM). PARM is essentially a simulation model using linear programming techniques for providing guidance to the Director of the Office of Emergency Planning in the Executive Office of the President on resource allocations and the coordination of economic mobilization plans among the major agencies of the United States government [4]. The model involves keeping

track of 1,007 distinct "activities" (or sectors) and approximately 94,000 time-dependent coefficients which describe the relationships among the activities. PARM is a very sophisticated input/output model of the type discussed previously in Section III. However, it is designed to fulfill the mission-oriented requirement of project selection and is therefore treated as a normative forecasting technique.

C. DECISION MATRICES

The most common use of a matrix in normative forecasting is for the optimization of resources under given constraints [1]. Resources in this context may be not only financial but may include manpower, skill, research or manufacturing resources. The matrix, in this case, represents an input/output matrix of scientific and technical effort in various fields.

An example of project selection based on two-dimensional resource matrices can be found at the Boeing Company [1]. First, one matrix is built for each project, showing the tasks and disciplines involved as one dimension, and the comparing resources as the other dimension. Projects corresponding to the given resource structure are then combined into higher-dimension matrices all the way up to "master" matrices for broad company activity areas. These "master" matrices are systematically used by Boeing as an auxiliary means of achieving optimum deployment of resources.

An example of a three-dimensional matrix, called "Program Cube Concept," and applied by International Minerals and

Chemicals, is described by Jantsch [1]. It has the three dimensions of market missions, resources and time. The resource dimension is structured into financial, personnel, marketing, sales, production, facilities, raw material markets, research and development, and public relations resources. Program planning in this illustration affects the whole cube. Whereas the market missions and resource dimensions, in a manner analogous to the Boeing concept, aid in optimizing the use of company capacity at a given moment, the dimension of time assures continuity of development in the various fields of interest.

D. NETWORK ANALYSIS

The network techniques, especially CPM (Critical Path Method) and PERT (Program Evaluation and Review Technique) are a management tool for the control of complex system design and production tasks. CPM is based on a "flow chart" scheme showing the different steps of all branches of the project. The branches are analyzed in order to select an optimum "path" between the first and the last stages, where the criterion for an optimum may be lowest cost, shortest time, etc. PERT, developed for the Polaris missile program, is a probabilistic approach characterized by an analysis of uncertain input data and input relationships (for example, uncertain time of completion of a sub-system) and the calculation of the probabilities of time and/or cost factors in the entire project. An excellent reference for the application of CPM and PERT to project selection is by Moder and Phillips [22].

In the analysis of the requirements for a project whose end point is well defined, the nodal points (events) of the network are specific activities. The first step of a network analysis, according to Ayres, is to identify all pertinent activities and their causal relationships and then draw the appropriate connections as directed lines on a chart [4]. The length of the lines in this case have no particular significance. The logically possible causal relationships between two events A and B are as follows: A is a prerequisite of B, B is a prerequisite of A, or none. In the latter case A and B are independent and can be carried out simultaneously or in any order which happens to be convenient.

Once the activity times are specified - either deterministically in the case of CPM or probabilistically in the case of PERT - the minimum total time for the project can be found by comparing the elapsed time of all paths through the network, and identifying the longest or so-called "critical path." On all other paths there is some leeway or slack time for adjusting the starting time to allocate scarce manpower resources most efficiently or to satisfy other constraints. This slack time for a particular activity is simply the difference between the earliest and latest possible starting times. Hence, one of the advantages of this method is revealed by the ease with which such questions as when to start an activity can be answered.

The complex series-parallel interrelationships found in the Polaris Missile Program, requires an extension of the

above discussion. The use of PERT is largely credited with the successful coordination of the several thousand contractors and agencies participating in the Polaris program, advancing the completion data by more than two years [23]. As a result of its success in the Polaris program, PERT techniques have been applied to such programs as the Air Force's Minuteman, Skybolt, Dyna-Soar, and B-70, the Army's Nike-Zeus, Pershing and Hawk, and the Navy's Eagle and Missileer. American private industry has also adopted PERT to assist in the management of projects which involve many interrelated activities [23].

E. RELEVANCE TREES

The relevance tree concept was first proposed by Churchman, *et al.* in connection with decision-making in general industrial contexts [24]. Ayres defines a relevance tree as a logical network designed explicitly to elucidate the degree of importance of various "inputs" (e.g., projects) to a broadly defined outcome or goal [4]. Questions which can be elucidated with the assistance of such a "tree" include optimum allocation of fixed resources to maximize the value of research and development and the optimum selection of research and development program content. Where the objective is a specific one which has already been labeled a "program" - as in the case of controlled thermonuclear power - a tree of prerequisites and alternatives is a possible starting point for a critical path network analysis associated with a detailed plan of action.

The relevance tree approach is particularly well suited for guiding decisions involving a large number of technological alternatives such as weapon systems, new product developments, and research projects. It can be explained and discussed best by describing a particular model for facilitating such choices.

The first large-scale application of relevance trees to numerical analysis for decision-making has been made by Honeywell's Military and Space Sciences Department. The process is called PATTERN, an acronym for Planning Assistance Through Technical Evaluation of Relevance Numbers [25]. PATTERN consists of three basic parts. First, a relevance tree which measures the relative importance to the national objectives of upgrading a particular mission or technical area. Second, status and timing which measures industry's capability to solve the identified problems. Third, cross support which measures the degree of technical growth that will result from solving a specific problem.

A scenario which projects the world environment (including military, political, and economic factors) and a comprehensive state-of-the-art technological forecast are used as basic inputs in the evaluation process. A team of experts using decision criteria and subjective probability techniques, assign quantitative values relating to the importance of upgrading that item in terms of its contribution to meeting the overall national objectives for the time period in question. Cross support and status and timing factors are also assigned numerical values. These numerical

inputs are then fed into a computer program and the output of a model "run" is a set of relevance numbers (or relative priorities) for listed projects, systems, or technologies in terms of its relative importance to the national military stature as compared to all other areas used in the evaluation process.

The relevance tree used in PATTERN is basically a structured decision network consisting of eight levels beginning with national security objectives and progressing through types of conflicts, forms of conflicts, missions, systems concepts, functional subsystems, subsystem configurations and technology deficiencies, in a tree-like organization. The structure of the general relevance tree is shown in Figure 9.

The structure is first divided into three major parts. At the top, in the political and ideological area is where the President and the National Security Council make policy-type decisions. The second level, the conceptual and requirements area, is the level where the Secretary of Defense, the Administrator of NASA, and the individual Service Chiefs make decisions. The third level, the technology area, is where the individual service laboratories and the laboratories of industry make technical decisions.

The basic three-part structure is then sub-divided into the various levels shown on the right of Figure 9 plus the national objective level, making a total of eight levels. In order to make value judgments in the horizontal plane at

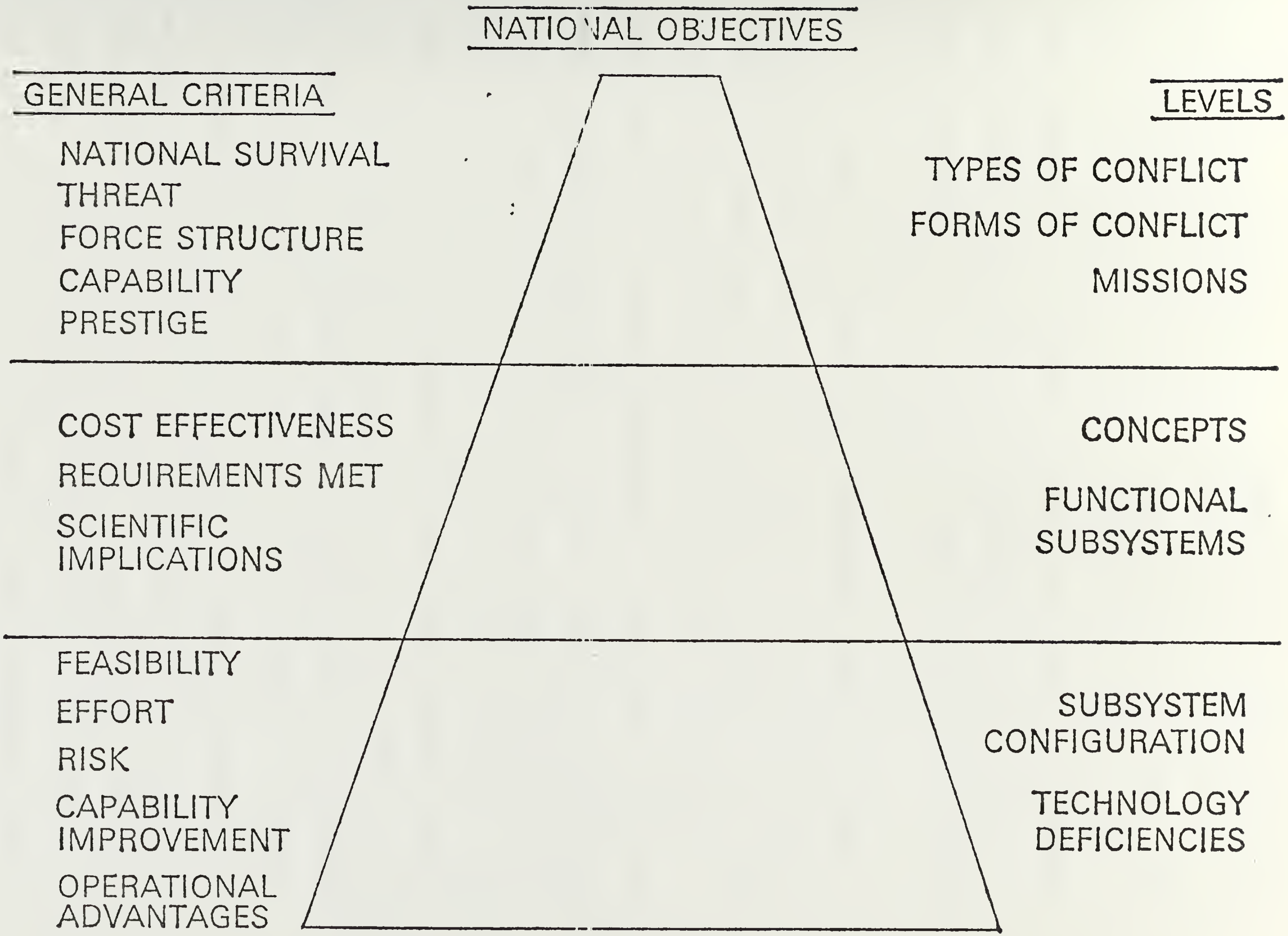

Figure 9. General Relevance Tree of PATTERN.

each level of the tree, it is necessary to apply rigid definitions to each item on the tree as well as to develop a set of ground rules (criteria) for the situation at hand. Key words representing the various criteria are shown on the left of Figure 9. In developing the criteria, it is important to ensure that they are appropriate to the level at which the decision is to be made and that they are mutually exclusive in so far as possible.

In order to explain the terminology associated with relevance trees, the top four levels of the overall structure are broken down into finer detail in Figure 10. This figure is characteristic of the "tree-like" organization associated with decision analysis. At the top is the United States' National Objectives. The next level indicates the various types of conflict where challenges to our National Objectives may be expected, e.g., military activities, noncombat activities and exploratory and civil support activities. The next level indicates the form that these challenges may take, i.e., various types of limited wars, intelligence, arms control, etc. Under each of these forms of conflict is a spectrum of missions in which a capability must be developed and maintained if the Government is to counter the challenge in each specific area of competition. The obvious advantage of this type of detailed structure is that it divides the large many-faceted problem into small segments and permits one to make comparisons among small numbers of items at any single level. At the same time, the capability of again

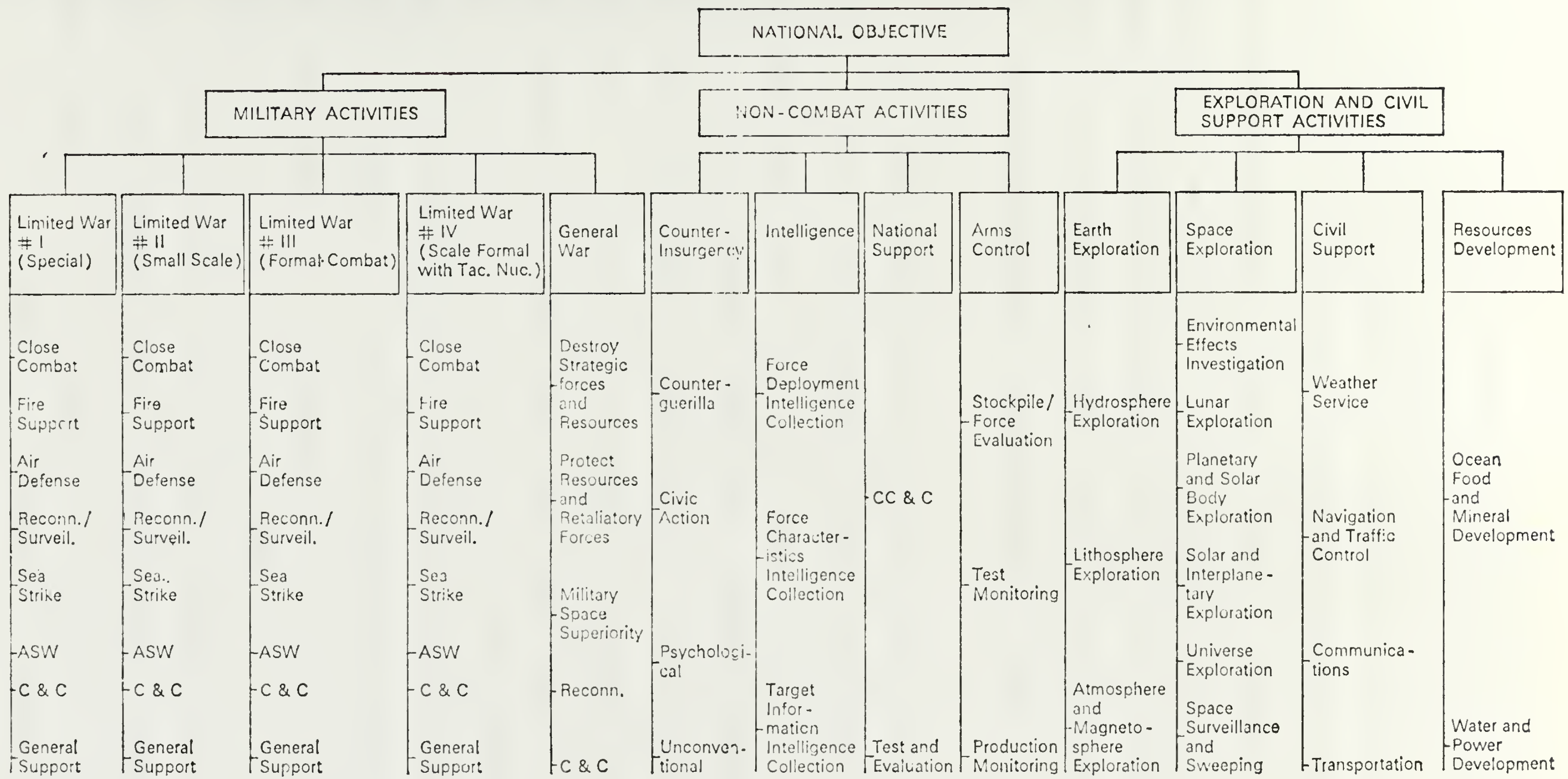

Figure 10. Detailed Relevance Tree of the Top Four Levels of PATTERN.

looking at the total package as an entity is retained once the individual value judgments have been made.

Referring to Figure 10, relevance numbers are assigned at each node of the tree by teams of experts using carefully selected criteria as a base for their judgments. The basic procedure is to employ a value judgment matrix using mathematical techniques developed for decision-making under conditions of uncertainty. For a detailed explanation of these mathematical techniques the interested reader is advised to consult Reference 25.

The lower four levels of the overall structure (Figure 9) are also divided, starting with postulated concepts as the fifth level. At the sixth level each of the concepts divided into seventeen functional subsystem areas together with associated requirements needed to meet concept performance goals. In most cases there are several alternative ways by which the functional subsystem requirements can be met. These alternate methods are called subsystem configurations and constitute the seventh level of the structure. Contained within the competing subsystem configurations are the technological deficiences to be solved. These deficiences represent the eighth and final level.

The second major part of the PATTERN has to do with the status and timing of the technology needs. Once the needs of the Government are assessed an evaluation of the capability of industry to achieve the technical solutions to the identified problems is the next order of business. To initiate this step a comprehensive technical forecast using several

exploratory forecasting techniques is conducted and an assessment is made of the current status of several hundred technologies, as well as the likely rate of improvement in performance of each technology area over time. PATTERN then uses this evaluation of the status of technology and its projected rate of growth in determining the time and capability required to meet the previously identified national technical needs. These data are then inserted at the functional subsystem and technical deficiency levels in the tree and indicate the capability of the country to meet its military/exploratory type technology needs.

The third major part of PATTERN consists of the cross support information. Cross support as defined by Honeywell, represents the total gain in technical capability, across all subsystem areas, accumulated by working in a specific subsystem problem area. Time is used as the common denominator and a zero to one scale is used in assigning the cross support values. Thus, the subsystem configuration cross support number represents the degree to which solving a specific technical problem on a particular subsystem configuration reduces the effort needed to solve similar or related subsystem problems.

The flexibility of the PATTERN concept is demonstrated by its application in other areas. For example, Honeywell management initiated a study to identify present and future needs in bio-medicine [25]. Honeywell also prepared a relevance tree for NASA's Apollo Program [1]. Approaches very

similar to PATTERN have been or are being applied to strategic decision making in a number of industries and organizations, notably by Swager [1] and Cetron [3]. Fields combines the relevance tree concept with morphological analysis and the Delphi method to establish a general procedure for technological forecasting [26].

The author is of the opinion that the real values of the relevance tree scheme is in combination with other methods such as the method proposed by Fields [26]. The most prominent example of the application of the relevance tree concept in combination with other forecasting techniques is that of the Planning-Programming-Budgeting System (PPBS) of the U. S. Department of Defense. The PPB System is built around a four-level decision-tree concept which is closely related to the relevance trees discussed earlier. Other operations research/systems analysis techniques and the Delphi method are used in conjunction with relevance tree techniques.

V. CONCLUSION

The three previous sections of this paper have been devoted to a discussion of the various techniques employed in technological forecasting. It must be remembered, however, that forecasting in general is beset by hazards, simply because the future is not known. Most of these hazards, e.g., the uncertainty and unreliability of data, apply to all forms of forecasting. In addition, the literature suggests there are some pitfalls pertinent to technological forecasting. It seems appropriate at this time to point out some of these major pitfalls, since improper use of the available techniques may lead to misdirected goals and wasted resources.

A bold prediction of large increases in unknown functional capabilities requires considerable imagination on the part of forecasters. A common pitfall, especially among so-called committees of experts, is a lack of this imagination. This particular problem is usually in the form of the failure to see converging technical developments, the acceptance of trends as rigidly continuing, the reliance on limited information, and concentration on specific configurations of technology now in use. A classic example cited by Ayres is that of the committee selected in 1940 by the National Academy of Sciences to evaluate the proposed gas turbine [4]. The committee's reasoned and careful conclusion, based on many conservative assumptions, was that gas turbines would have to weigh 13 to 15 lb./hp compared with

1.1 lb./hp for internal-combustion engines then operating. In point of fact, a gas turbine was in operation one year later with a weight of 0.4 lb./hp.

On the opposite side of the spectrum there are individuals of scientific bent who maintain that given the resources, time, and motivation, the human intellect can create virtually anything it can conceive. This type of pitfall can be remedied by the forecaster if he does not attempt to predict to the "nth" limit or too far in advance. Again, Ayres cites some interesting examples of this optimistic attitude [4]. For instance, using the envelope curve for vehicular speeds it appears that the speed of light would seem to be achieved by 1982. Another equally ridiculous example of overcompensation is that derived from life-expectancy trends. From these trends forecasters have predicted that anyone born after 2000 A.D. will live forever, barring accidents of course.

Aspects of future scientific progress can also be poorly estimated because of a lack of consideration of seemingly unrelated factors, such as resistance to change by vested interests, public inertia, unforeseen costs, available resources and lack of understanding of new technologies. Many research and development programs of a few years ago which induced great expectations failed to have a truly significant effect on the present environment. Nuclear powered aircraft and the relatively slow advancement of nuclear power for non-military use are typical examples.

In addition to the foregoing pitfalls, it must be recognized that mistakes in methodology are also cause for concern. The use of inappropriate techniques or incorrect calculations can lead the forecaster to some rather interesting conclusions. Consider, for example, the calculation made by the Canadian astronomer, J. W. Campbell, that a moon rocket would have to weigh one million tons in order to carry one pound of payload [4]. This calculation was off by six orders of magnitude due to unrealistic assumptions about fuels and failure to take multiple staging into account.

Many technological advancements depend to some degree on basically unpredictable elements such as luck or coincidence, individual insight, personal drives and various other personality traits. In fact, the creative process in humans, which is probably the greatest force for the advancement of technology, is not yet completely understood and should, in this author's opinion, be the subject of more intensive study.

Given that various techniques and their associated pitfalls exist, the natural question to address at this point is what should be considered in selecting a method. The forecasting techniques discussed in the three previous sections ranged from intuitive to statistical to cause and effect analysis to means of structuring the information in order to examine interrelationships and consider alternatives. The techniques presented have varying degrees of complexity and usefulness. None is a magic formula or an all-purpose

device and each has its advocates and adversaries. The point to keep in mind is that all can be useful. The technique which is "best" depends upon the circumstances under which the forecaster is working and his needs; the reliability, completeness, and quantitative precision of the data base; the purpose of the forecast; the length of the forecast period; and the time available for generating the forecast. In general, the level of treatment should correspond to the importance and level of complexity of the problem area. The technique selected should be compatible with and adaptable to the available information.

Conversely, there appears to be a very real need for improvement in the level or degree of sophistication with which many technologies are treated by forecasters. For example, the most unsophisticated forecasting technique in use today is the individual type. It has been estimated that a large percentage of all forecasting done by the military services is of this type [3]. Frequently, insufficient historical data preclude the use of more sophisticated techniques. However, in this author's opinion, there are many instances where substantial quantities of reliable data are available for analysis but are not used. As a result, the level of confidence which can be ascribed to the forecast is frequently less than desirable.

The literature suggests that the major requisites of good forecasting can be reduced to: (1) the knowledge of scientific and technical specialists in the subject matter

area; (2) astute judgment and common sense on the part of the forecaster; and (3) a technical understanding of available forecasting methods and how and when to apply them. The primary gain from the use of such techniques is a greatly improved insight into the nature and interrelationships of influencing factors and the sensitivity of solutions to these factor variations. These techniques also provide the possibility of evaluating, within a consistent frame of reference, distinct alternative technical solutions to a given operational problem. In effect, the techniques provide the tools whereby the technical knowledge and judgment of the forecaster can be applied to logical, systematic thinking about the pattern of development of the particular technology.

The best forecast for a given purpose may require the use of various methods, i.e., a combination of intuitive, exploratory, and normative techniques. The several forecasts provide a range of probable developments, they may be combined to give a single estimate of the future, or they may provide a choice of predictions according to the purpose for which it is intended. A recent example of this approach to forecasting is offered by Fields [26]. Fields made a preliminary study of the techniques currently being used and recommended that a combination of the Delphi technique, morphological analysis, and the relevance tree technique be used. In addition, many experts in the technological forecasting business agree with Fields and suggest that for most

applications some combination of the available techniques is best.

In spite of the wide choice of techniques and knowledge of the pros and cons of these techniques, the author of this paper is of the opinion that the practice of technological forecasting is as yet, not well developed. Furthermore, among those practioners that do develop formal forecasts, there is little evidence of effective integration with planning.

Examples of useful technological forecasts are scarce because of widespread resistance or neutrality towards the subject. This is due in part to the disadvantages, limitations and pitfalls of the various techniques as discussed in the preceding paragraphs. However, the primary reason why technological forecasting only goes as far as "lip-service" is because of a general lack of understanding of the nature of change.

The greatest benefit of forecasting lies in its use as guidance for the activities of organizations. In particular, the forecast should help the planner make correct decisions. It is imperative then that key individuals in an organization identify all areas of change important to their organization and even more important that they interpret the potential impact that an observed change may present. The nature of change, however, presents problems which organizations have been unable to overcome with formal forecasting techniques. The problematic task of forecasting all possible

changes that may occur in the technical, political, and social environments surrounding an organization appears to be more difficult than the literature suggests. The mere accusation that management suffers from a "lack of imagination" does little to solve the problem.

If an organization is to prepare for the future, it is not merely a question of adopting one or more of the various techniques and applying it according to generally accepted principles. It is much more a question of recognizing and understanding the nature of changes in technology and its associated effects on all the environments surrounding the organization. Since forecasting efforts are directly related to the decision-making process, failure to allow the results of forecasts to affect the plans of the organization may undersell a potentially powerful tool. Until these difficulties are resolved, they will continue to severely limit the applicability of the formal forecasting techniques.

The past decade has brought a new attitude toward the future in public and private planning agencies. This change has extended customary planning horizons to a more distant future and replaced haphazard "fortune-telling" techniques with objective analysis. There is a growing awareness that a great deal can be said about future trends in terms of probability, and moreover, that through proper planning, these probabilities can be influenced considerably. The author of this paper suggests that further research should be devoted to understanding the structure of the stochastic

process involved in technological forecasting. In particular, such probabilities as the conditional probability of a successful technical solution given the required resources and the probability that these required resources will be made available, should be considered.

If the author of this paper may be permitted a prophecy about technological forecasting, the next decade will see a host of conferences with great stress on resolving the nature of change and its resulting impacts. This author forsees increasing use of formal technological forecasting techniques and predicts that forecasts will look further and further into the future. This longer look, coupled with the acknowledgement of the non-technical environment, will force a thorough integration of technological forecasting with the decision-making process.

APPENDIX A - ANNOTATED BILBIOGRAPHY

"Technological Forecasting in Perspective," an international survey of technological forecasting conducted by Dr. Erich Jantsch, is based on eight months of research in thirteen countries [1]. The volume contains an annotated bibliography with over 400 literature references. The text begins with a set of definitions and basic concepts. Part 2, A Framework for Technological Forecasting, is highly conceptual and philosophical. While Part II, Techniques Related to Technological Forecasting is mathematically oriented. Part III, Organization of Technological Forecasting, presents the findings of Dr. Jantsch's search for applications. Although the author of this paper found sections of the book difficult to read, it is recommedned for any reader interested in technological forecasting.

"Technological Forecasting for Industry and Government," edited by James R. Bright, contains the proceedings of the First Annual Technology and Management Conference [2]. The volume covers a broad range of topics discussed by several well-known experts in the field of management. This author found this book relatively easy to read and it too included an annotated bibliography.

"Technological Forecasting: A Practical Approach" is written by Marvin J. Cetron and is based on his experience with the Department of Defense [3]. As a result, many of the concepts and ideas are illustrated with military examples.

Cetron draws several analogies between military programs and business situations thus giving the reader a broader view of the domain of technological forecasting. The author's organized, list-making style is very readable; and his annotated bibliographies are extensive.

"Technological Forecasting and Long Range Planning," by Robert U. Ayres, provides an excellent description of the methods employed in exploratory forecasting [4]. While the mathematical sophistication may be difficult for some readers, they are not crucial to understanding the methods, and should not prevent the reader from appreciating the use of a large number of industrial examples.

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13. ABSTRACT

A critical survey of technological forecasting techniques is presented. The nature of technological forecasting permits the various techniques to be classified as intuitive, exploratory, and normative. Intuitive technological forecasting is based on the informal use of exploratory and normative techniques, including the forecaster's biases and hunches. Exploratory technological forecasting starts from a present empirical or theoretical basis of knowledge and is oriented towards the future. Normative technological forecasting, on the other hand, first assesses future goals and missions and works backward to the present. Some pitfalls of technological forecasting are discussed. The most essential are: (1) a lack of imagination on the part of the forecasters; (2) a belief that the human intellect can create anything it can conceive; (3) a lack of consideration of seemingly unrelated factors; and (4) the use of inappropriate techniques or incorrect calculations. Factors which should be considered in selecting a forecasting technique are suggested and include: (1) the circumstances under which the forecaster is working; (2) the characteristics of the data base; (3) and the time available for generating the forecast.

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